https://ntrs.nasa.gov/search.jsp?R=20170010684 2019-08-31T01:37:14+00:00Z

Transformational Solar Array
Final Report

For the interval July 19, 2016 through April 26, 2017
Issue date: April 26, 2017

by

Edward Gaddy
Space Exploration Sector
Johns Hopkins University Applied Physics Laboratory
11100 Johns Hopkins Road
Laurel, MD 20723-6099

(240) 475 4599
edward.gaddy@jhuapl.edu

NNC16CA19C
Game Changing Development Program
Extreme Environments Solar Power Project

Prepared for NASA Glenn Research Center, Cleveland, OH 44135

This report is suitable for public dissemination

.

Table of Contents

Authors

While this report is formally authored by Edward Gaddy,
much of the work was performed by:

- Mihaela Ballarotto, Christian Drabenstadt, and John Nichols at the Applied Physics Laboratory (APL)
- Mark Douglas and Brian Spence at Deployable Space Systems (DSS)
- Richard A. Stall at Newforge Technologies
- Chris Sulyma and Paul Sharps at SolAero

Transformational Array Performance at the Conclusion of the Base Phase

Item	NRA Goal	Transformational Array Performance	Percentage of NRA Goal
BOL Cell Efficiency	35 %	33.7 %	96 %
EOL Blanket Efficiency	28 %	28.3 %	101 %
Specific Power at LILT	8 - 10 W kg^{-1}	9.52 W kg^{-1}	95 %
Packaging Density	60 kW m^{-3}	51.4 kW m^{-3}	86 %
Survive Launch Conditions	Required	To be demonstrated by Option II per plan	0%
Operate from 100 – 300 V	Required	To be demonstrated by Option II per plan	0%
Operate in Plasma Exhaust Fields	Required	To be demonstrated by Option II per plan	0%

We have made outstanding progress in the Base Phase towards achieving the final NASA Research Announcement (NRA) goals. Progress is better than anticipated due to the lighter than predicted mass of the IMM solar cells. We look forward to further improvements in the IMM cell performance during Option I and Option II; so, we have confidence that the first four items listed in the table will improve to better than the NRA goals. The computation of the end of life blanket efficiency is uncertain because we have extrapolated the radiation damage from room temperature measurements. The last three items listed in the Table were not intended to be accomplished during the Base Phase; they will be achieved during Option I and Option II.

Section I: Technical Progress Summary

Description of the Transformational Solar Array

The Transformational Solar Array uses Deployable Space System's (DSS) Roll Out Solar Array (ROSA) as a structure and equips the array with very high efficiency SolAero Inverted Metamorphic (IMM) solar cells and reflective concentrators. Figure 1 is a photograph of a ROSA array without concentrators. Figure 2 is a photograph of a concentrator equipped power module.

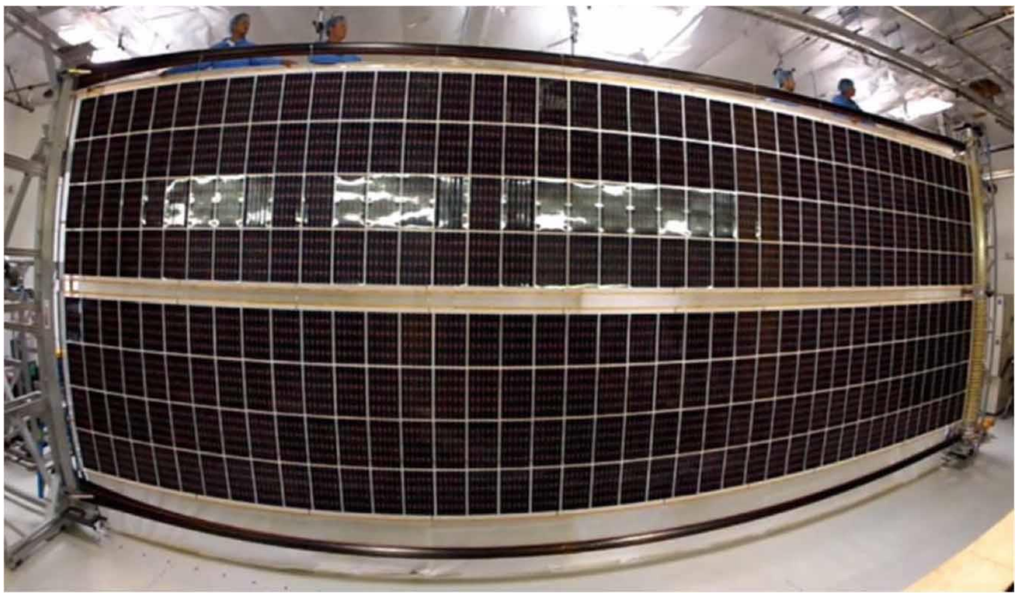

Figure 1: A ROSA Solar Array

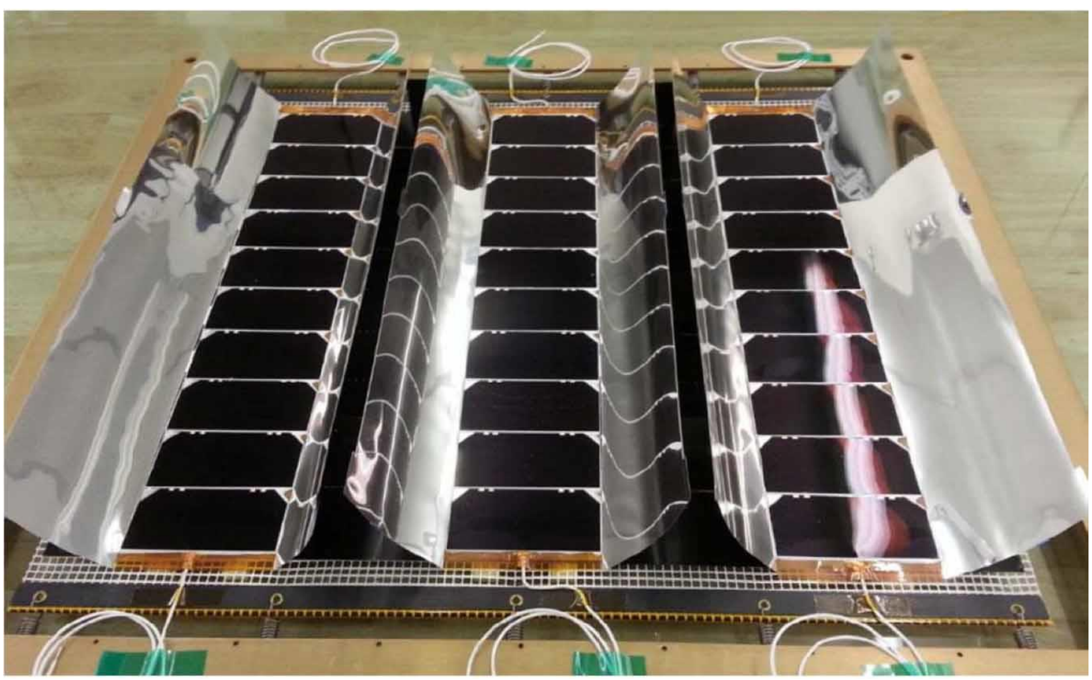

Figure 2: Concentrator equipped power module

Detailed description of major system components

The MM solar cell is at the heart of the Transformational Solar Array. These cells have the potential to achieve exceptionally high efficiencies; and during the Base Phase of the program they already attained an efficiency of 33.7% under standard test conditions. In addition to high efficiency, the IMM cell with its carrier is 40% lighter than the SolAero state of the art ZTJ solar cell. Figure 3 is a schematic of an IMM6 solar cell. The cell is grown inverted, as shown, with lattice matched high band gap junctions grown first, followed by metamorphic buffers and then metamorphic, with respect to the higher band gap junctions, lower band gap junctions. During subsequent processing the cell is inverted, attached to a carrier of cerium doped borosilicate glass with a polyimide, and the growth template removed.

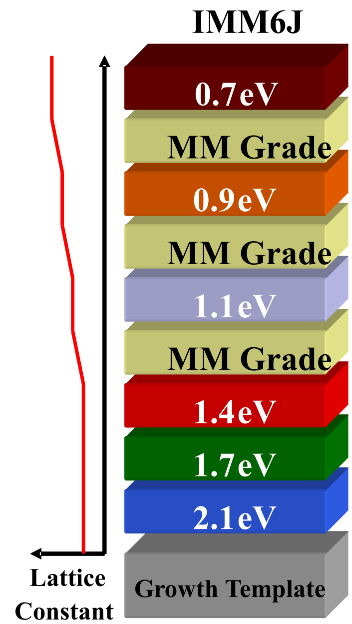

Figure 3: IMM6 Solar Cell

The coverglass selected for the Transformational Solar Array is 100 µm thick cerium doped borosilicate glass. This is the most commonly used coverglass for arrays. The coverglass to cell adhesive will either be 100 µm thick DC 93-500 or SCV2-2590 ultra low outgassing adhesive. The cell to substrate adhesive will be CV-2568 or possibly a pressure sensitive adhesive such as 3M 966. The latter will result in a less expensive array than one fabricated with CV-2568. The solar cell to substrate insulator will be the commonly used 50 µm thick Kapton.

The array substrate will be a fiberglass mesh having a low coefficient of thermal expansion. This will enhance the stability of the array. DSS has selected titanium for the substrate stiffener, and AWG 22 Raychem MIL-STD-1553 B wires for the harness. DSS will place foam strips on the backside of the blanket to provide damping and cell protection during launch vibration. A 25-kW wing will have about 90 blocking diodes placed on the array yoke.

The concentrator will be constructed with a 25 µm thick substrate, and coated with silver topped by SiO_2. An adhesion layer will be needed between the silver and the titanium. The materials that will make up this layer are to be determined. The mirror kick-up springs will be constructed of titanium as will be the stiffeners.

The array's deployment means will be two longitudinally oriented, thin-walled composite reinforced elastically-deployable slit-tube booms attached laterally at the tip and root ends with a mandrel and yoke structure respectively. These booms supply the deployment force from their stored strain energy. The blanket assembly is attached to the mandrel and the yoke and reacts against the compressively loaded booms. The tip mandrel is a hollow lightweight tube that provides synchronization between the booms and also serves as the surface onto which the blanket assembly rolls up.

The blanket assembly tensioners will be multiple constant force titanium leaf strings with sufficient stroke to maintain proper blanket tension and dimensional stability over the entire range of structural and thermal environments. There will be two blanket releases; one on each side of the mandrel. The tie down releases will be standard technology and placed as needed.

The Solar Array Drive Assembly (SADA) and slip rings will be a MOOG Type 5 with high power slip rings. The offset tube or yoke will be standard technology. The hinges will be standard technology at the end of the offset tube to allow the wing to rotate to service position. The control electronics, a two-channel unit from MOOG, will use signals from the spacecraft to command the SADA to rotate to an angular position. The electronics to be used to compute array angular position will be inside the spacecraft guidance and control (GNC) electronics. Of course, this location may vary depending on spacecraft manufacturer. The tie downs and releases will be standard technology Frangibolts. Aluminum brackets will be used to attach the ROSA to the spacecraft. The yoke panel or root support structure is a 125 mm by 75 mm by 0.75 mm thick wall structure.

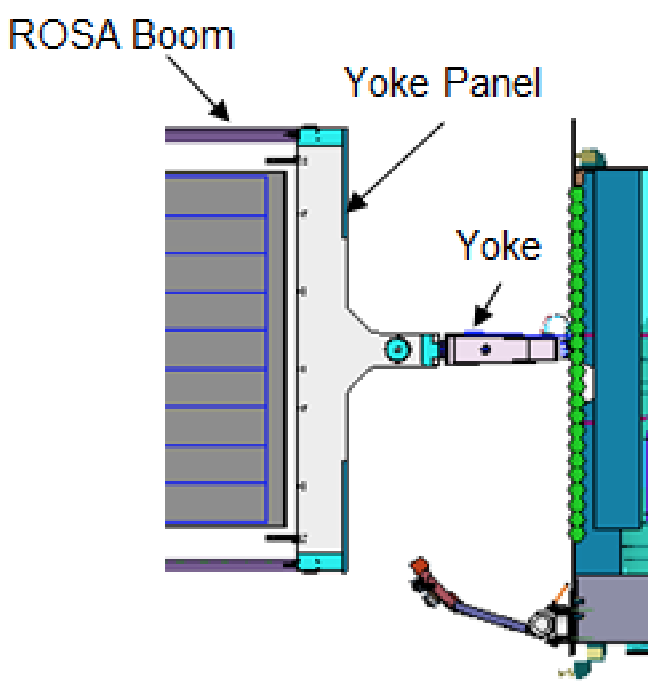

Figure 4: Solar Array Yoke and Yoke Panel

Goals

This report summarizes the work performed under the Base Phase of NASA contract NNC16CA19C. This work is directed toward meeting the goals of the associated NRA and, of course, the requirements of the contract. The NRA goals are:

1. Over 35% beginning of life cell efficiency at 5 AU and -125 °C
2. Over 28% end of life efficiency at the blanket level at 50 W m^{-2}, -125 °C and 4E15 1 MeV e cm^{-2}
3. From 8 - 10 W kg^{-1} (or over) at EOL for the entire array including structure, deployment, and pointing mechanisms
4. A stowed packaging density of 60 kW m^{-3}
5. An ability to survive launch
6. An array capable of operation over the range from 100 through 300 V
7. An ability to operate in a plasma generated by xenon thrusters, typically 1E8 cm^{-3} ions with an average energy of 2 eV

We believe our solution can ultimately exceed the NRA goals per the following:

1. Over 47% beginning of life cell efficiency at 5 AU and -125 °C using record-breaking inverted metamorphic solar cells
2. Over 32% end of life efficiency at the blanket level at 50 W m^{-2}, -125 °C and 4E15 1 MeV e cm^{-2}
3. A stowed packaging density of 66 kW m^{-3}
4. A design compatible with electrostatic and magnetic cleanliness
5. IMM solar cells that have no anomalous flat spot behavior at low irradiance and low temperature to improve production yields, thereby reducing costs
6. A mock-up production line for the low-cost manufacture of spacecraft blanket arrays

Plan to Meet the Goals at TRL-5 during Option I

Based on the achievements reached during the Base Phase, we believe that APL, SolAero, and DSS are well positioned to achieve TRL-5 for the Transformational Array while meeting the NRA goals.

Meeting the goals will require the use of IMM solar cells. These solar cells, which will be further developed in Option I, are already at TRL 7. They are flying on two Planet Labs CubeSats; and, SolAero plans to have these cells qualified to AIAA S-111 *Qualification and Quality Requirements for Space Solar Cells* in the Winter of this year under an AFRL funded ManTech program. These cells will come close to meeting the efficiency needed in Option I but require some additional development even though they are already at over 32% efficiency at standard test conditions. So, effort will be put into further increasing their efficiency during Option I. We also believe that the lighter weight of the IMM cells, compared to the ZTJ product, will ease the efficiency needed from the cells. Meeting the NRA goals in Option II will require the efficiencies available from IMM 6 solar cells. SolAero will further develop these cells during Option I. These cells are presently at TRL 4 as they have been fabricated and tested.

As reported herein, a fraction of the IMM solar cells exhibit shunts that affect their performance at Low Irradiance and Low Temperature (LILT) but not at air mass zero and more typical temperatures. If no action is taken to raise the yield of IMM cells by eliminating these shunts, the presence of the shunts will increase the cost to fabricate an array while not compromising the array's performance at LILT. Cells that have the shunts can be screened and removed from the flight population. Nonetheless, we strongly believe these shunts need to be eliminated for the Transformational array. During the Base Phase as reported in this document, the cause of the shunts was identified as growth particles; SolAero believes the number of problematic shunts in IMM cells can be substantially reduced based on their work that successfully reduced growth particles in prior generations of solar cells. Work on reduction of growth particles will be performed in Option I.

To be practical, IMM solar cells must be easily placed into strings. As the cells are so thin, this presented some uncertainty. However, SolAero has shown that it can be accomplished in an AFRL funded ManTech program. The company has already developed and demonstrated, with respect to IMM solar cells, automated manufacturing, robust interconnection methods, and reliable re-work processes. Indeed, the IMM is a "drop in replacement" for the ZTJ cells. In addition, strings of IMM cells have been flown. We believe that strings of IMM solar cells are at TRL 7. We do not believe additional work is required in this area.

Of course, the performance of the structure on which the IMM solar cells will fly is critical. As stated earlier, the Transformational Array uses ROSA for this structure. On another program, a 2-kW ROSA array has been fabricated and tested in an operational environment. This array is partially populated with solar cells including both Spectrolab and SolAero product. This wing has all the parts and equipment needed for flight and even has the ability to retract. We estimate this array to be at TRL-7. In addition, DSS plans to have a 14-kW array qualified for flight for SSL in September, 2017. So, the vast majority of the structure is already at higher than TRL-5. However, to reduce mass, the Transformational Array will use a stiffener, which is a replacement for the heat spreader-stiffener that the ROSA arrays described just above use. During the Base phase, DSS fabricated blankets with this stiffener. We estimate that the stiffener is at TRL-3. We believe that it will be straightforward and easy to bring the stiffener to TRL-5 during the Option I phase.

To meet the NRA technical goals, concentrators need not be used, so the use of this technology is a bonus that reduces cost. To this end, we are proposing Flexible Array Concentrator Technology (FACT). Excepting issues with outgassing and the reflector coating, the concentrator is already at TRL-6. APL proposes to guarantee concentrator performance by insuring that it is not contaminated with outgassing, and by better adhering its reflective coating to the mirror structure. We intend to work on these items in Option I. We are also aiming to make the mirror nonmagnetic. In part, these goals are achieved by using titanium as the mirror substrate rather than stainless steel. The titanium substrates have already been fabricated in the Base Phase.

In short, nearly all of intended components for the Transformational Array are already at a high TRL level. To finally obtain the end product that meets all of the performance goals only requires incremental improvement in components that already exist. Therefore, we have high confidence that our solution will succeed.

More plans for Option I are in Section IV, Work Planned.

Risks Associated with Meeting TRL5+ at the End of Option II

Overall, APL asserts that the likelihood of meeting TRL5+ at the end of Option II is good. The greatest risk with meeting the goal is associated with achieving a very high efficiency IMM solar cell. While the development of IMM solar cells has been to this point in time quite challenging and slow relative to the development of previous cells, this is primarily due to learning how to handle, interconnect and otherwise process the extremely thin cells. During the past year or so SolAero has successfully demonstrated that they can handle, interconnect, and process the cells. With that hurdle behind them, they can concentrate on developing higher efficiencies and radiation resistance.

To that end, SolAero has analytically designed cells with the efficiency required to meet contract goals using existing materials. We therefore believe that it is a matter of learning how to fabricate the cells. This is, of course, non-trivial but it is doable. In addition, we are already at over 95% of the needed cell efficiency for two of the first three goals and over the efficiency needed for one goal. This is indicative that we will be successful at the end of Option II.

We believe the next most challenging development is reducing outgassing contamination of the concentrators and we believe there is a high probability of meeting this goal at TRL5+ at the end of Option II. There are at least three different paths to meeting the goal and all of them appear to have a high likelihood of success. These are pre-treating the adhesives used on the solar cell assemblies with heat, loading the adhesive with microspheres, and physically blocking the adhesive from reaching the concentrator mirrors. During the Base Phase, DSS successfully fabricated thermoformed shields that will block outgassing.

The final development required is fixing the mirror reflective coating so that it adheres to the mirror substrate during environmental exposure. No work was performed in this area during the Base Phase; but, APL's experts in this area believe that this is doable.

Considerations on Placing the Transformational Array onto a Space Flight Mission

To have a project select the Transformational Array, the project must believe that the array: is ready to use without further development, has substantial advantages over the state of the art, will not over-run contracted cost, will meet contracted schedule, be demonstrably reliable, and, while perhaps be more expensive considering its technical advantages, be price competitive. APL selected technologies for the Transformational Array that will meet these requirements. The ROSA array, which forms the structure for the Transformational Array is already being considered for use by SSL for some of its Geostationary Spacecraft. In addition, APL itself has base-lined a ROSA array for the Double Asteroid Redirection Test (DART) spacecraft, which is to be ready for launch in December, 2020. (This mission includes an ion propulsion system similar to that required for use on the Transformational Array.) DSS has delivered a 2 kW BOL size wing to the Air Force for the ISS-based TRL-8/9 flight experiment currently scheduled for launch on the SpaceX-11 Dragon in April or May of 2017. The state of these missions, at the end of the Option II Phase, will provide confidence that the structure for the Transformational Array is: fully developed, ready to use, at a high TRL level, and possesses sufficient heritage for reliable pricing and scheduling.

APL selected IMM solar cells for the Transformational Array knowing that other government agencies are funding development of the cells for manufacturing readiness. Again, this means that the IMM cells will be at a high TRL level and SolAero will have performed substantial research demonstrating that their cost and schedule estimates are compatible with a flight program and likely to be met.

APL has selected reflective concentrators for the Transformational Array. While these are not yet ready to be used on a flight program, we believe that they will be ready at the end of Option II. By this time, APL will have run significant and thorough Qualification Tests demonstrating that outgassing and reflective surface delamination issues have been solved. Furthermore, APL intends to qualify blanket samples to AIAA S-112, *Quality and Qualification Requirements for Electrical Components on Space Solar Panels*: including Acoustic, Electrostatic Discharge, UV Exposure, Thermal Vacuum Exposure, Thermal Cycling, Output as a function of angle, and Solar Cell Assembly Characterization. We intend to make these Qualification Tests convincing and thorough.

Finally, a mission to 5 AU will almost certainly be scientific. This means that there is a high probability that the project will require a solar array that is magnetically and electrostatically clean. The ROSA array with IMM solar cells and concentrators is compatible with these requirements with some minor design changes. These changes will likely include removal of the eddy current deployment speed control with a replacement centrifugal brake control, back wiring of the cell strings, and ITO coating on the wing coverglasses. We have not included these in the Transformational Array technology hardware as these are not required by the NRA.

However, we will address these areas with designs; and, if possible, include some of them into hardware.

APL believes that the Transformational Solar Array will be ready for use on Flight Programs at the end of Option II and that it will be a formidable competitor to any other arrays based on its performance, its TRL level and its heritage. We intend that the additional steps required to utilize the Transformational Array on a flight program will be similar to those required for any other array. Namely, the Transformational Array will need to have some mechanical alteration to securely mount to the spacecraft so that it survives launch vibration and will need to be sized to fit the spacecraft and the mission.

Summary of Base Phase Work

The base phase of the project was primarily directed to meeting the goals associated with low cost production of the array, cell efficiency improvement, and blanket mass reduction. The first sub-goal to these goals was to determine if IMM cells exhibited flat spots at Low Irradiance Low Temperature (LILT), and if they did, to eliminate the flat spots. The concern with these is that they reduce power to an unacceptable value. While IMM cells with flats can be screened, added production costs due to low yield needs to be minimized. The second sub-goal was to effectively eliminate outgassing of solar cell adhesives as this impairs the performance of concentrator mirrors. The third sub-goal was to lighten the blanket by eliminating its heat spreader, which is not necessary at 5 AU.

To address the first sub-goal SolAero fabricated and tested IMM solar cells for the presence of flat spots. SolAero found no flat spots, which is a significant finding. They did find shunts in approximately 30% of the solar cells at LILT, which is also an important finding. By the by, these shunts did not materially deteriorate I-V performance at 1 sun and room temperature. SolAero has determined the cause of the shunts and believes that their number can be substantially reduced based on methods already developed to solve the same problem in prior generations of SolAero cell products.

To address the second sub-goal, APL measured the outgassing rates of various adhesives and adhesive configurations, including some pre-treated with heat. These measurements gave some encouragement to configurations and pre-treatments that would effectively reduce outgassing to acceptable levels. Newforge Technologies manufactured an LED simulator needed to induce cover glass adhesive outgassing with UV.

To address the third sub-goal, DSS successfully redesigned the blanket for the replacement of the heat spreader with a titanium sheet stiffener. DSS also computed power outputs for different ROSA sizes.

Technical progress in the Base Phase

IMM Solar Cells

Summary

IMM solar cells were fabricated and tested

The average efficiency of the IMM cells under standard test conditions (STC) was 33.7%

The average efficiency of the IMM cells at 5 AU and -125 °C was 36.2%

Shunts were discovered and determined to be due to growth particle that would affect yield. SolAero has experience in successfully reducing growth particle contamination.

SolAero tested twenty 38 IMM solar cells.

Figure 5 shows the current versus voltage curve of two IMM solar cells, 001B and 006A, at 1 sun and 28 °C. Figure 6 shows current versus voltage curves for the same two cells at LILT: -125 °C, and 0.04 sun. Cell 006A shows a substantial degradation at LILT but not at 1 sun. Approximately 30% of the cells show a similar defect as cell 006A at LILT. During the proposal writing and the first several months of the contract and in agreement with industry understanding, APL had assumed that the defect that the IMM cells might exhibit at LILT was a flat spot, similar to that seen in silicon solar cells and state of the art three-junction GaAs-based solar cells such as SolAero's ZTJ cell. SolAero's work showed that the flat spot did not manifest in IMM cells. What was discovered instead were solar cells that exhibited a definite shunt at LILT. This did not change the course of research that SolAero originally planned, namely, to determine the cause(s) of any defect and then pursue a cure. The same would have occurred had the shunt been a flat spot.

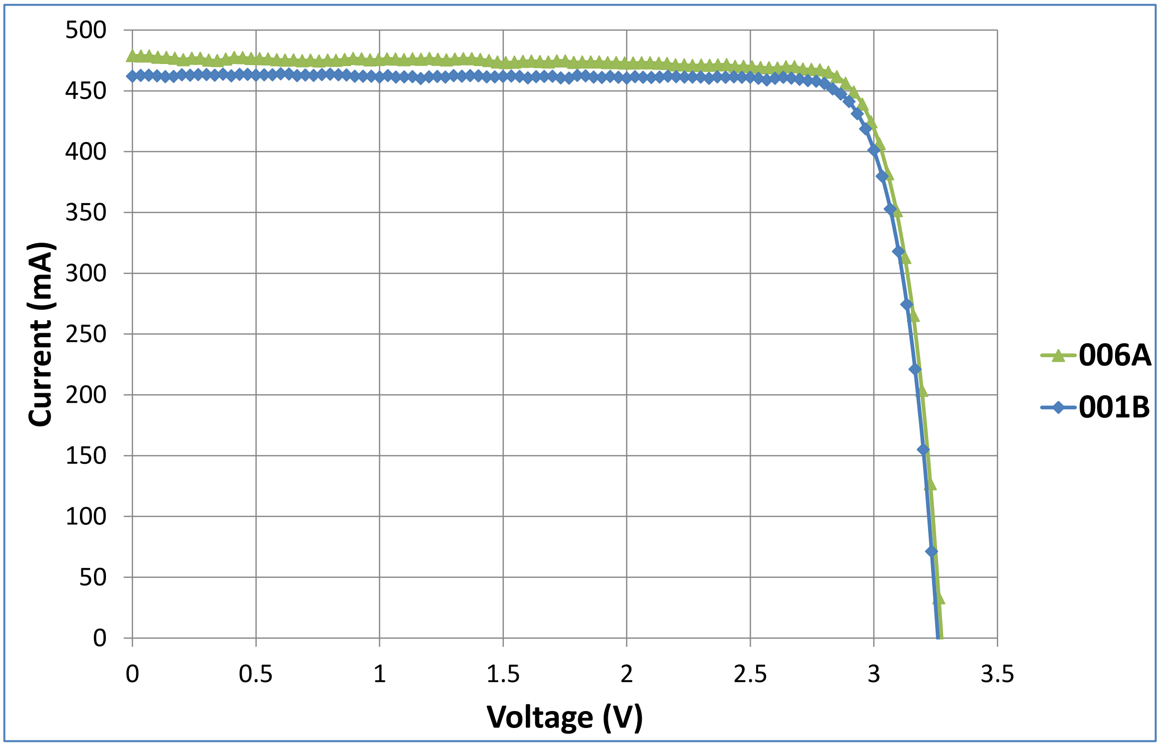

Figure 5: Output of Two IMM Cells at 1 Sun and 28 °C

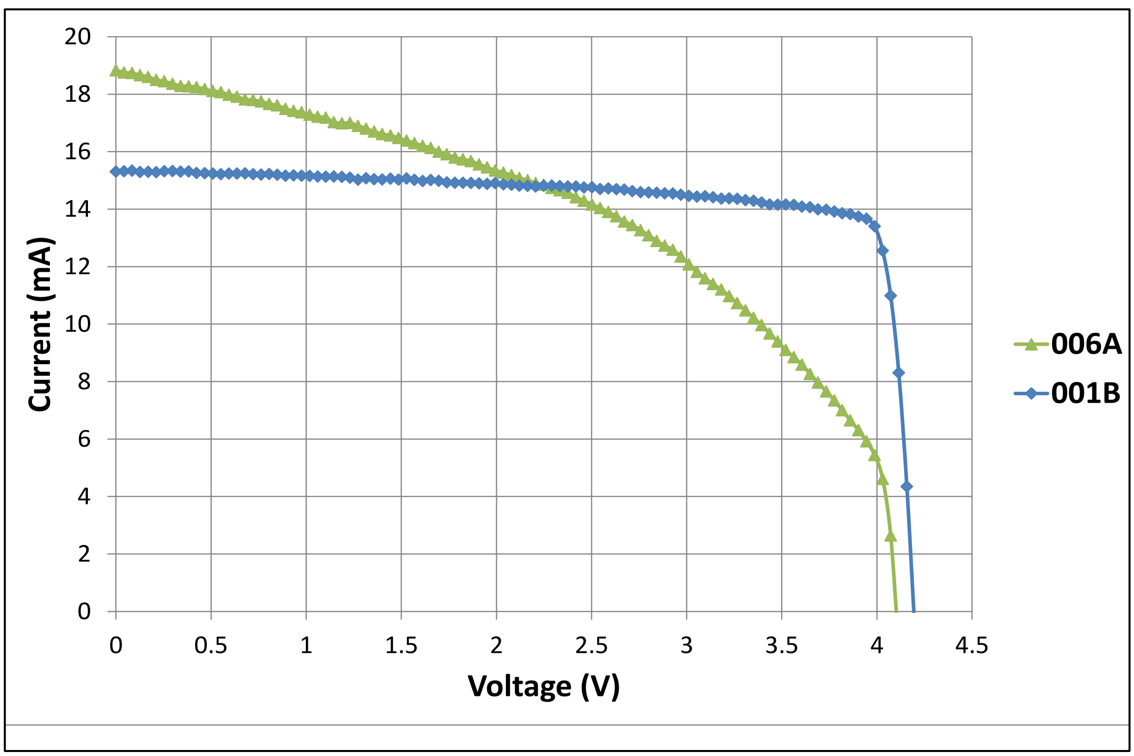

Figure 6: Output of Two IMM Cells at 0.04 Sun and -125 °C

SolAero determined that the cause of the shunts was growth particles. During the growth process, when epitaxial layers are being deposited, particles from the walls of the Metal Organic Chemical Vapor Deposition (MOCVD) reactor can "flake" and deposit on the growth surface. If the particle is large enough, and if it is deposited near the start of the growth process, it can extend through all of the semiconductor layers. Smaller particles may only extend through part of one of the layers. SolAero has performed considerable work to eliminate and minimize the growth particles on their products but they still occur. The effect of the particles varies, depending on their size, as well as how the solar cell is operated. At lower currents, such as in LILT operation, a cell will be more sensitive to the leakage currents (shunts) from the particles. When growth particles have an effect on cell performance they can be seen in electroluminescence (EL). They can also be seen by optical microscopy. Figure 7 shows both an optical and an EL of an IMM cell that has a shunt. Figure 8 is a higher magnification picture of the defect, which corresponds to a growth particle near the grid line.

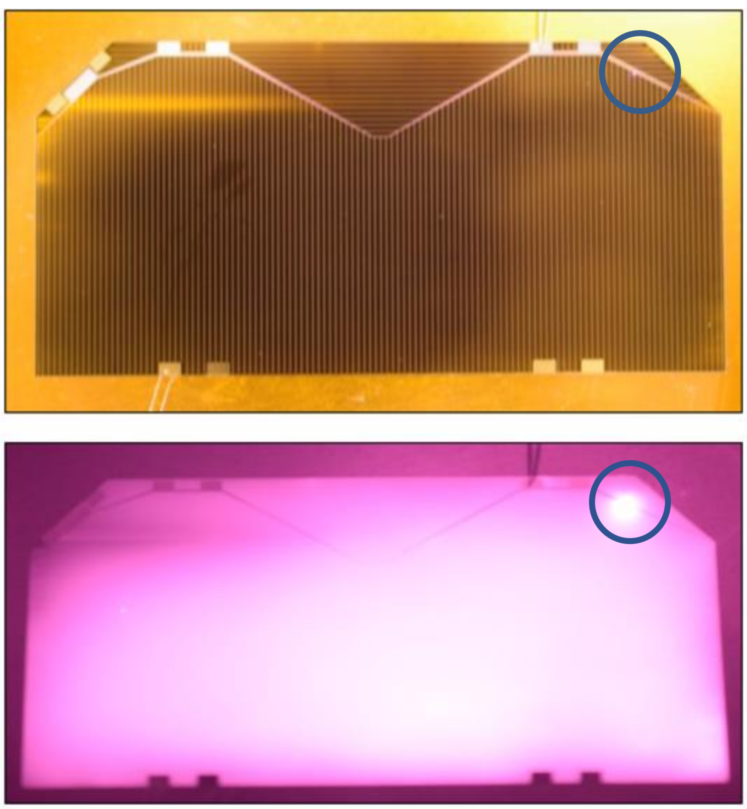

Figure 7: Optical picture (top) and electroluminescence (EL) (bottom) of cell 234934-03A showing location of the shunt

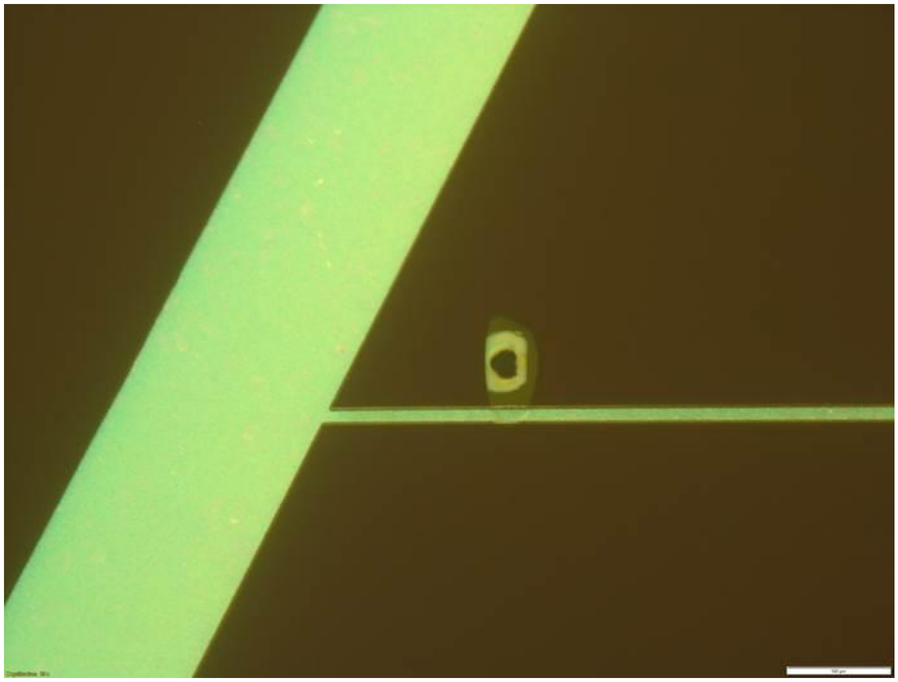

Figure 8: Growth particle and etching pit corresponding to the bright EL spot in Figure 7

SolAero has been working for many years to minimize growth particle issues, through modifications to the growth reactors, the growth platters that hold the substrates, and the loading and unloading processes. During the transition to the ATJ triple junction cell a number of years ago the yield was significantly improved through particle reduction. In addition, all of SolAero's space flight cells are visually screened for such defects under or near front grid metallization. Any cell with such a defect is excluded from flight hardware, so there is no technical risk to the performance of the final flight solar array.

SolAero is already addressing this issue in other programs. This work will benefit the Transformational Array. SolAero is currently taking three steps on an IMM ManTech program to reduce the impact of growth particles and increase IMM yield. First, improvements to the growth reactor loading and unloading processes are being studied. Secondly, a modification to some of the etching steps, which would reduce the etch pit such as seen in Figure 8, are being explored for improvement. And thirdly, a lithography process for isolating such defects is being considered. SolAero believes that as the IMM cell ramps to production and a larger number of IMM cells are made much more scrutiny will be given to improving IMM yield. This will significantly reduce the shunts that affect LILT performance even though the cell performance is much more sensitive to shunt issues due to the low irradiance. At present, there can also be variability in the severity of the problem from growth lot to growth lot. One growth lot had 6 of 20 cells that showed the shunting at low intensity, while another lot only had 2 of 18 cells that showed the issue. This is an indication that the problem can be substantially mitigated.

The SolAero testing is done at a conservative 0.04 suns or even less. The Transformational Array's concentrators will cause the cells to operate at approximately 0.08 suns. We expect that this will slightly lessen the effect of the shunts and will confirm this in Option I.

Outgassing

Legacy equipment and the design and fabrication of additional equipment to determine outgassing

Summary

One of APL's legacy thermal vacuum chambers was modified to run outgassing tests

An effusion cell that directs outgassing product to a TQCM in a controlled manner was designed and fabricated

A UV LED solar simulator was purchased to expose adhesive samples to UV

The APL legacy Combined Environment Thermal Vacuum Chamber (CEnT) is a 180-cm diameter by 71-cm deep stainless steel chamber equipped with a 25-cm diameter cryogenic pump that has an ultimate pressure in the 10^{-9} Torr range. The chamber is thermally controlled by a 58-cm diameter by 41-cm deep black chrome plated stainless steel shroud. The shroud has a temperature range of -190 to 200 °C. For outgassing measurements, a 15 MHz Thermally Controlled Quartz Microbalance (TQCM) is used. The chamber door has an ISO 250 adapter flange to configure equipment and sources as required. The CEnT chamber was reconfigured for outgassing tests to use a 365nm UV LED thermally controlled light source. A 28-cm diameter by 2.3-cm thick quartz window was attached to the ISO flange. Two cartridge heaters are mounted on the quartz window with a design that enables heating of the quartz to >100 °C while allowing high optical access into the chamber. Figure 9 is a photograph of the chamber.

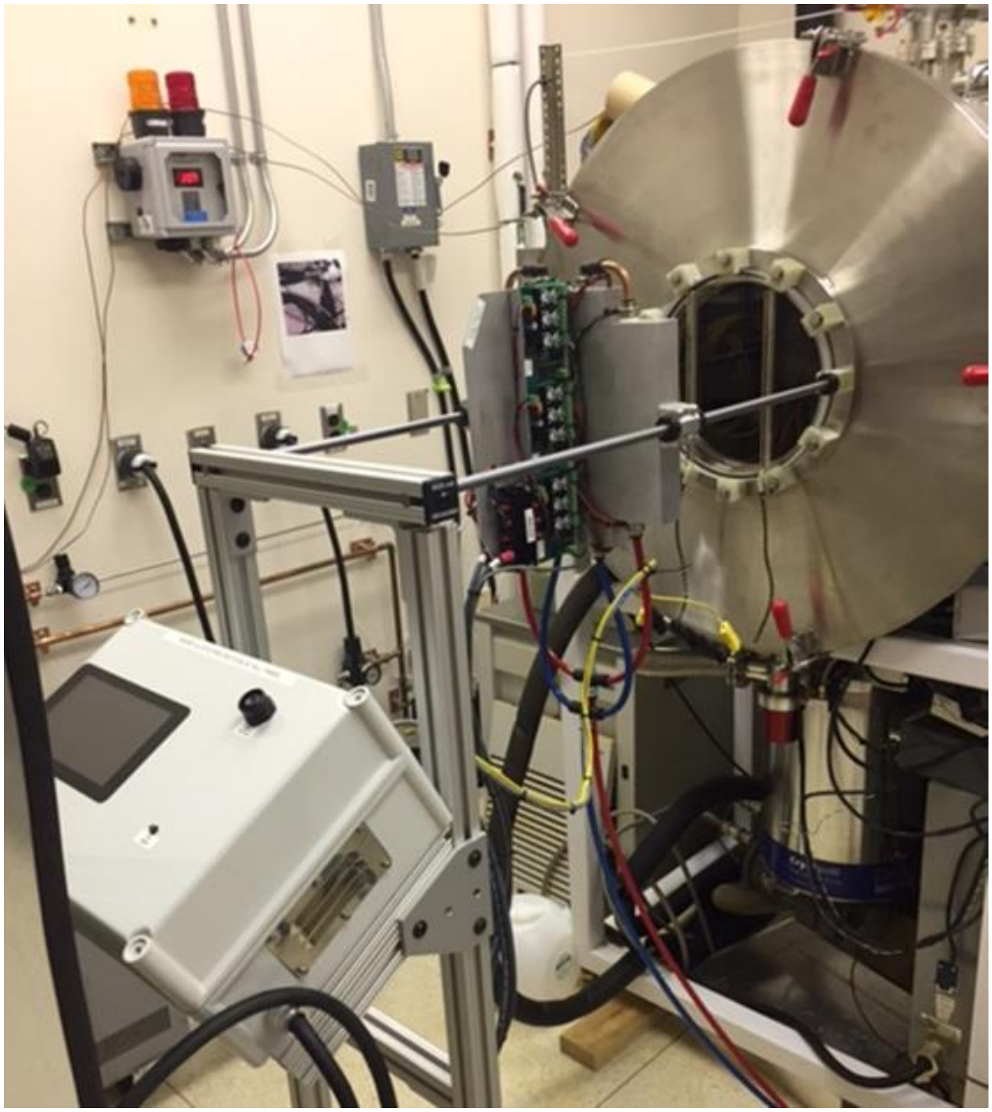

Figure 9: APL Combined Environment Chamber (CEnT)

In the Base Phase, APL designed and manufactured an effusion cell to be used in outgassing tests. Figure 10 is a photograph of the cell mounted in the vacuum chamber with heater cartridges attached.

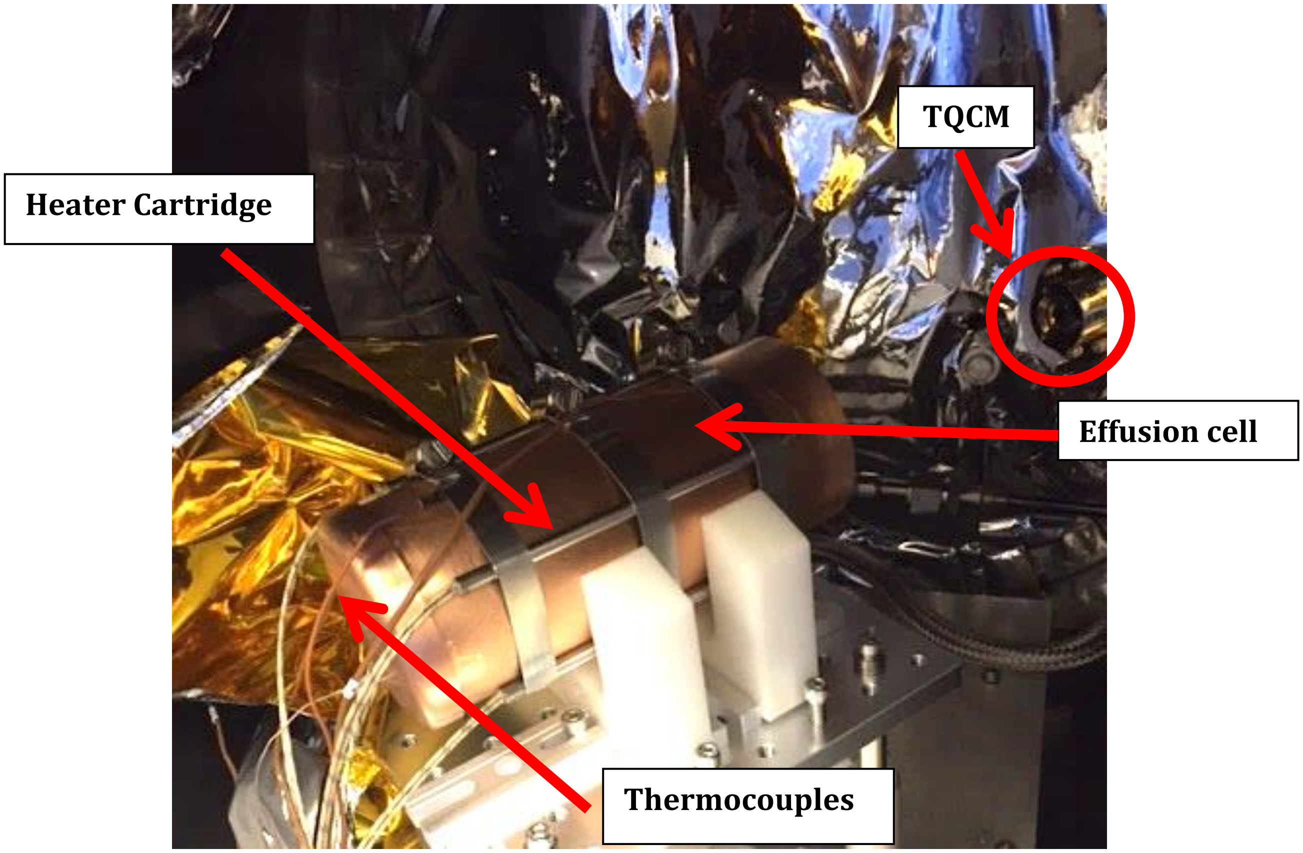

Figure 10: Effusion cell mounted in vacuum chamber

The purpose of the effusion cell and its single opening is to collect most of the outgassing and direct it toward the TQCM.

The effusion cell is a uniformly heated copper cylinder placed in the vacuum chamber, as can be seen in Figure 11. It has a cylindrical orifice such that outgassing species exit the cell in a controlled manner. The effusion cell dimensions and orifice size are specified such that there is free molecular flow and predictable molecular flux from the orifice. The total mass loss (TML) of material outgassed from the test specimen maintained at a specified constant temperature and operating pressure can be calculated from the mass deposited on a cooled TQCM, knowing the view factor from the effusion cell orifice to the TQCM.

Figure 12 is a photograph of the sample holder. This is positioned into the effusion cell so the flat side is up and suitable for the placement of the sample. Figure 13 shows the effusion cell opening. This is "pointed" at the TQCM.

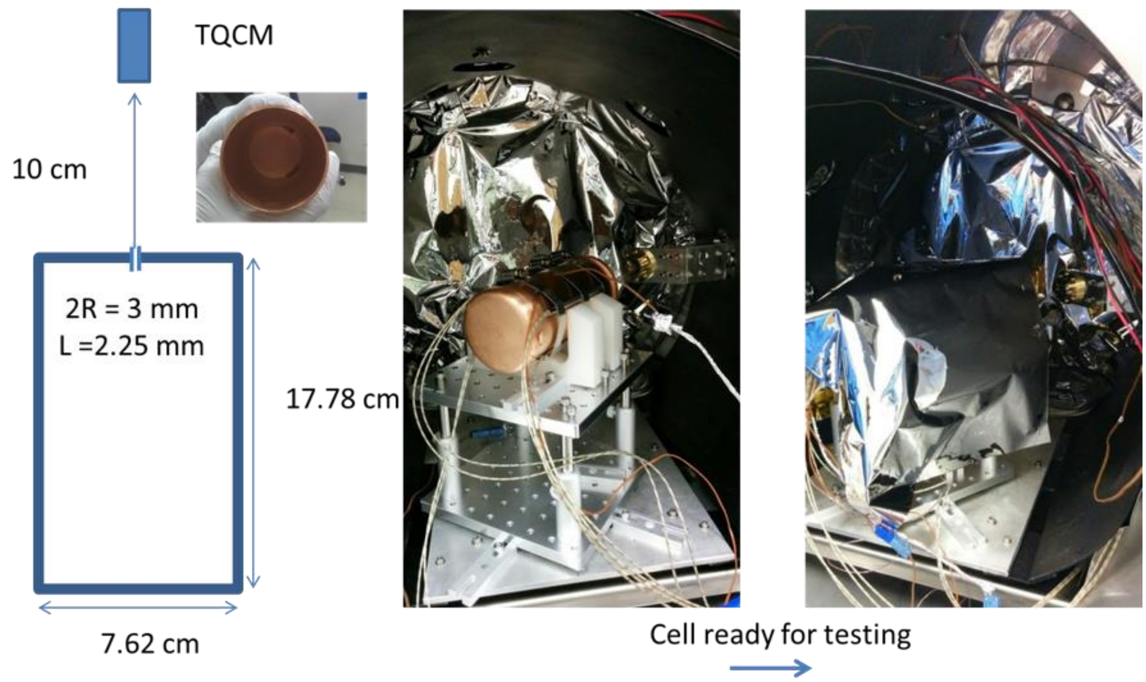

Figure 11: Effusion cell - TQCM geometry

In addition to the above, APL installed a custom-made 365nm UV LED solar simulator and tested its performance. This simulator, purchased with APL capital, was obtained to expose UV samples to ultra-violet light. The reason for this derives from results from the testing of SCAs for the Solar Probe Plus by Rick Stall and others. Namely, UV can cause substantial outgassing of adhesives even when they are protected by coverglasses.

The outgassing of materials caused by UV is in addition to the outgassing of volatile materials through heat, which has been studied in the Base Phase work for the Transformational Array. The material that is outgassed is a silicone oil that is created by the breaking of the chemical bonds in the silicone under UV. The silicone oil is volatile above approximately 100 °C and thus can be particularly troublesome for concentrator system. If not properly designed from an outgassing perspective, a concentrator system could have the mirrors at a temperature significantly lower than 100 °C while the solar panel is above 100 °C. Such a thermal environment will lead to silicone oil being created under solar intensity and desorbing from the solar panel with this silicone oil being collected on the cooler concentrator. Even more problematic is that the collected silicone oil will darken under prolonged exposure to UV. This implies that it may not be sufficient to pre-condition a solar cell assembly for low outgassing by heating it to a high temperature, without UV, until its outgassing asymptotes; subsequent exposure to UV will result in additional substantial outgassing of silicone oil. Initial testing on the SPP program did show a drop in the mass of an SCA through a "24 hour" thermal bake at 150 °C in the dark and then a larger drop on the same SCA after a subsequent UV bake at 150 C for 24 hours. The UV LED simulator was purchased to test this finding in more detail.

Figure 12: Sample holder that sits within the effusion cell (prototype shown)

Figure 13: Effusion cell opening (prototype shown)

A photograph of the UV LED simulator is shown in Figure 14. The control box, with its touch screen display is shown in the photo. The simulator cold plate, onto which the UV LEDs are attached, is mounted onto two horizontal bars that run from the vacuum chamber's quartz window and that enable the UV LED simulator to be retracted 46 centimeters. This mechanism allows for irradiance measurements to be made with a calibrated UV photodetector mounted on the atmospheric side of the viewport but with the same, "46 centimeter" separation of the LED arrays to sample area in the vacuum chamber. (The effect of having to transmit though the quartz viewport does reduce the 365nm intensity by approximately 10%. The quartz material is chosen to have high UV transmission at 365 nm.) The UV LED simulator is water cooled to enable a highly stable UV intensity. Figure 15 is a photograph of the simulator's six LED boards and their temperature controlled heat sink onto which they are attached.

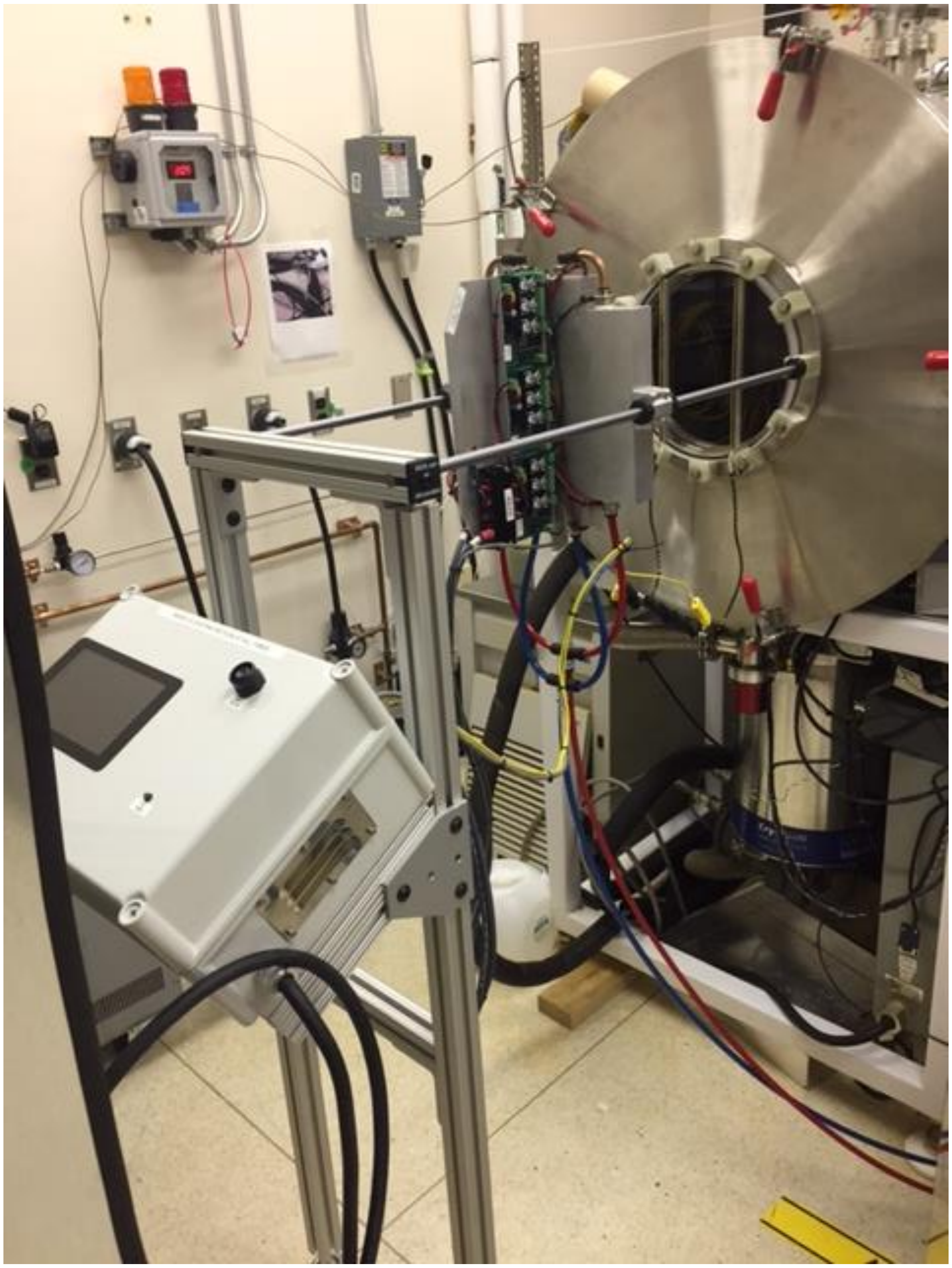

Figure 14: LED Solar Simulator attached to an APL vacuum chamber.

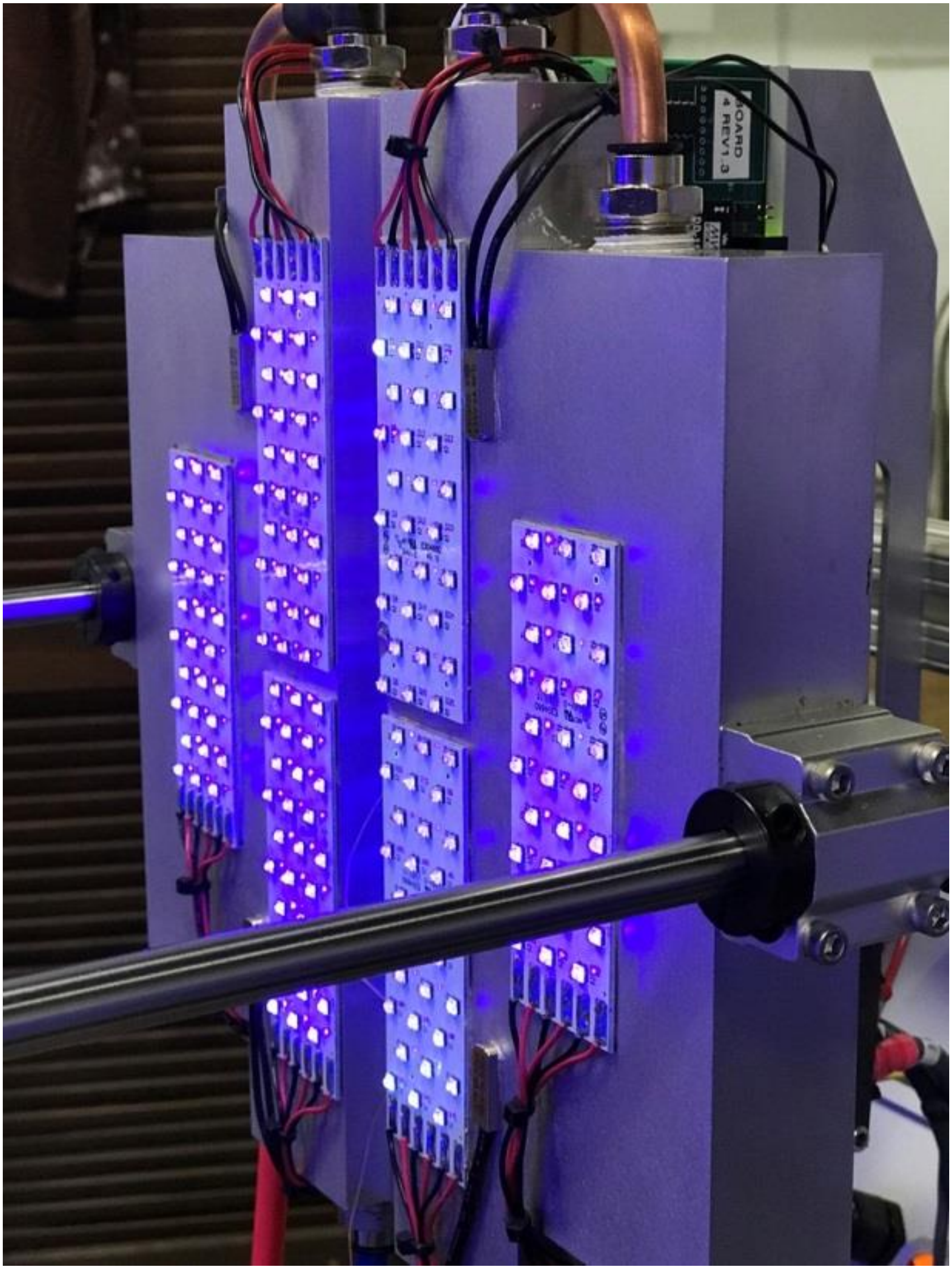

Figure 15: Simulator UV board arrays and thermal heat sink

Outgassing testing

Summary

Single Solar Cell Assemblies (SCA)s do not generate enough outgassing product to be measurable in the laboratory

60% of the desorption contaminant from an uncovered sample can be captured in 10 days of bake out

An Ultra-Low Outgassing coverglass to cell adhesive does outgas less than the heritage adhesive

The coverglass to cell adhesive loaded with 33% microspheres only decreases cell output by 0.4% relative to an SCA fabricated with pure adhesive

The APL approach will be able to estimate mirror contamination by outgassing in Option I

The objective of this work is to minimize outgassing contamination on the concentrators that is generated by the coverglass to cell adhesive on the Transformational Solar Array. We tested Dow Corning's DC 93-500, the most common coverglass to solar cell adhesive, and SCV2-2590, a Nusil Technologies product that substitutes for DC 93-500 and that promises ultra-low outgassing. We have also investigated two pre-treatments to reduce outgassing: thermal bake-out of the adhesive at 150 °C, and thermal bake-out of the adhesive while exposing it to UV at a temperature of ~100 °C.

Thermal vacuum bake out is one of the principal tools to mitigate outgassing contamination. For the Transformational Array, we need to definitely determine whether such bake-out is sufficient and if so what temperature and interval are required. We will complete this in Option I.

In the bake-out process, the volatile compounds are removed at temperatures higher than the nominal maximum on-orbit operating temperatures. The testing in the Base Phase focused on characterizing at 150 °C. We looked at outgassing of uncovered DC 93-500 with no microspheres and uncovered SCV2-2590 with no microspheres. We also tested DC 93-500 that was covered with borosilicate glass.

The outgassing process can be characterized with three different mechanisms: desorption, diffusion and decomposition. Desorption is the release of surface molecules into the gas phase. It has a strong temperature dependence and the outgassing rate decreases in time as t^{-1} to t^{-2} [1]. Outgassing in vacuum occurs predominantly via diffusion of molecules through the bulk of the material towards the free surface where they escape. This occurs as $t^{-0.5}$. Decomposition is the chemical division of a compound into two or more byproducts, which are subsequently removed through desorption or diffusion.

The rate of mass loss due to outgassing can be expressed as:

$$\frac{dM}{dt}(t,T) = C\, e^{\frac{-E_a}{RT}}\, t^{-n},$$

where:

C is a material constant depending on the initial state of the sample or shape or molecular mass,
E_a is the activation energy for the mechanism controlling the outgassing process
R is the gas molar constant
T is the temperature in K
$f(t) = t^{-n}$ is the analytical function determined by the rate limiting mechanism.

Our scope is to identify the $f(t)$ describing the rate limiting mechanism for our samples in an effort to predict the impact of certain outgassing pretreatments on collected volatile condensable material on a cold surface.

Our first attempt to run outgassing tests was on a number of SCAs that SolAero fabricated. The SCAs did not emit sufficient outgassing product for detection by the APL TQCM. The weight loss on one of the SCAs tested was 140 µg. The SCA contained approximately 0.435g of adhesive. About 0.03% of the adhesive outgassed by weight. APL outgassed another SCA with the result that about 100 µg of adhesive outgassed, about a 0.02% loss of adhesive. Again, insufficient outgassing product was emitted for measurement.

As a result of the discovery of the inability to measure outgassing from the SCAs, we requested that SolAero manufacture additional samples with more adhesive to characterize outgassing on a mass percentage basis and to then extrapolate back to the thinner flight SCAs. To further insure measurable outgassing, these samples were initially either pure adhesive pucks or adhesive fixed to silicon wafers with no cover glass. Later, samples with relatively thick adhesive were covered with borosilicate glass.

The mass density deposited on the TQCM at a given temperature is given by the equation:

$$\frac{d(-\Delta f)}{d(\Delta m/A)} = 2\,\frac{f_0}{\sqrt{n\mu_q}} = S,$$

where:

f_0 is the crystal resonant frequency

Δf is the frequency change
$\Delta m/A$ is the mass change per unit area on the active crystal area,
n is the density of the quartz
μ_q is the shear modulus of the crystal surface
S is the crystal sensitivity.

The direct relation between the mass accumulated on the crystal surface and the variation in frequency is $\Delta m = 6.2083 \times 10^{-10}$ (g/Hz) $\times$ Δf (Hz).

The mass deposited on the TQCM is related to the mass that has been emitted from the effusion cell through the TQCM-to-effusion cell orifice view factor *F*. The view factor was calculated for our geometry using the formula provided by the Standard Test Method for Contamination Outgassing Characteristics of Spacecraft Materials, ASTME 1559-09. The calculated F was 117.48 cm^2, corresponding to a 10-cm distance from the orifice to the TQCM crystal, and an orifice transmission probability of 0.5810, as defined by the orifice geometry (diameter of orifice 2R = 3 mm, length of orifice L = 2.25 mm, as depicted in Figure 11).

The in-situ total mass loss TML in g cm^{-2} from the sample can be expressed as:

$$TML(t) = F\,\frac{m(t)}{A_s}\ ,$$

where m is the mass deposited on the TQCM and A_s is the area of the sample. The time-dependent outgassing rate, *OGR(t),* is computed by differentiating the in situ *TML(t)*. The data can also be reported as Collected Volatile Condensable Material or *CVCM(t)*, representing the in-situ total mass loss *TML(t)* as percentage of the initial mass of the outgassing sample.

The samples used in this work were tested following these steps:

- Record mass of sample before loading it inside the vacuum chamber
- Stabilize shroud temperature at 25 °C and load sample
- Evacuate chamber to 5×10^{-5} Torr and stabilize TQCM at -20 °C
- Heat effusion cell to 150 °C while recording TQCM frequency and effusion cell temperature
- Vent, remove sample, and record the mass of the sample immediately and after 24 hours to identify total mass loss (TML)

Outgassing Analysis

With the initial data generated we extrapolated the CVCM and the outgassing rate over an interval of many years. However, the outgassing's three mechanisms, desorption, diffusion, and dissociation, will occur at different times that may not be adequately represented in the test protocol used in the Base Phase. This work will continue in Option I to ensure that the long-term effects of the outgassing mechanisms are fully characterized.

Typical TQCM frequency data as well as TQCM and sample temperature data recorded during an outgassing experiment is illustrated in Figure 16. The frequency data is corrected for baseline, or noise level outgassing, corresponding to an empty chamber and a clean effusion cell. The baseline is recorded before starting the test. The frequency data is further separated on data collected while the effusion cell is ramping up to the desired temperature (T<150°C) and data corresponding to a constant temperature T = 150°C. The outgassing rate (OGR) at T = 150 °C is subsequently evaluated for a power low dependence, OGR (t) ~ t^{-n}. A linear fit of the log(OGR) versus log(t) allows for the extraction of n as the slope of the linear fit.

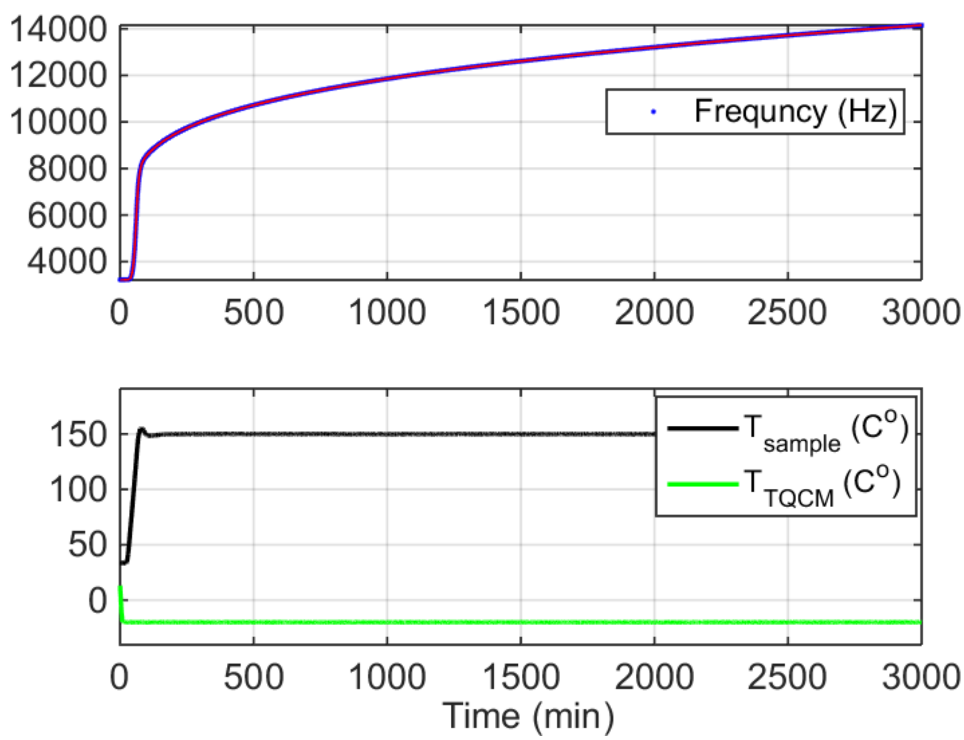

Figure 16: TQCM frequency data and monitored temperature for DC 93-500 sample and TQCM

Figure 17 through Figure 23 are all with reference to three samples. Sample 2 is uncovered DC 93-500 with a mass of 1.203 g, Sample 13 is uncovered SCV2-2590 with a mass of 1.163 g, Sample 7 is DC 93-500 covered with borosilicate glass with a mass of 1.424 g.

In Figure 17, the TQCM frequency data for DC 93-500 sample 2 is presented where the blue curve is the uncorrected frequency as a function of time. The green and red curves are after subtracting the baseline. The green curve occurs as the sample ramps to 150 °C from room temperature and the red curve is while the sample is at 150 °C.

From the data in Figure 17, APL has extracted the outgassing rate at 150 °C and identified the power law dependence of the OGR(t) as is ~ t^{-n}. This is shown in Figure 18, where the linear fit of the log(OGR) as a function of log(t) is presented, and n is extracted as the slope of the linear fit. Figure 19 is CVCM% as a function of time for sample 2. When the data in Figure 19 is extrapolated to 1 year, the CVCM% is 0.14%.

Figure 19 shows that uncovered DC 93-500 emits more than 0.03% CVCM just by increasing the temperature to 150 °C. The functional dependence of the OGR(t) from Figure 18 is $t^{-0.93}$ suggests we are mostly capturing outgassing corresponding to a desorption process, which is outgassing from surfaces [1]. By extrapolating the data for 1 year the expected CVCM corresponding to this process becomes 0.14%. A thermal treatment at 150 °C for 10 days would eliminate about 60% of this outgassing as shown in Figure 20. It is important to know if it were the majority of the emitted product in our application; which will be investigated in Option I along with diffusion driven outgassing, which may be the main contributor to the CVCM in a long interval.

For practical application, the DC 93-500 with coverglass does not have a large free surface to outgas. The volatile compounds present in the bulk and on the surfaces at the interface with solar cell and coverglass would have to diffuse to the edges of the sample to outgas. The figures show that uncovered samples, which were chosen because they provided a large outgassing signal, are not adequate for our purposes because they emit more product from desorption than would a covered sample and this desorption swamps the product emitted from diffusion. The later would likely be the largest contributor to the contamination of the mirrors in practice.

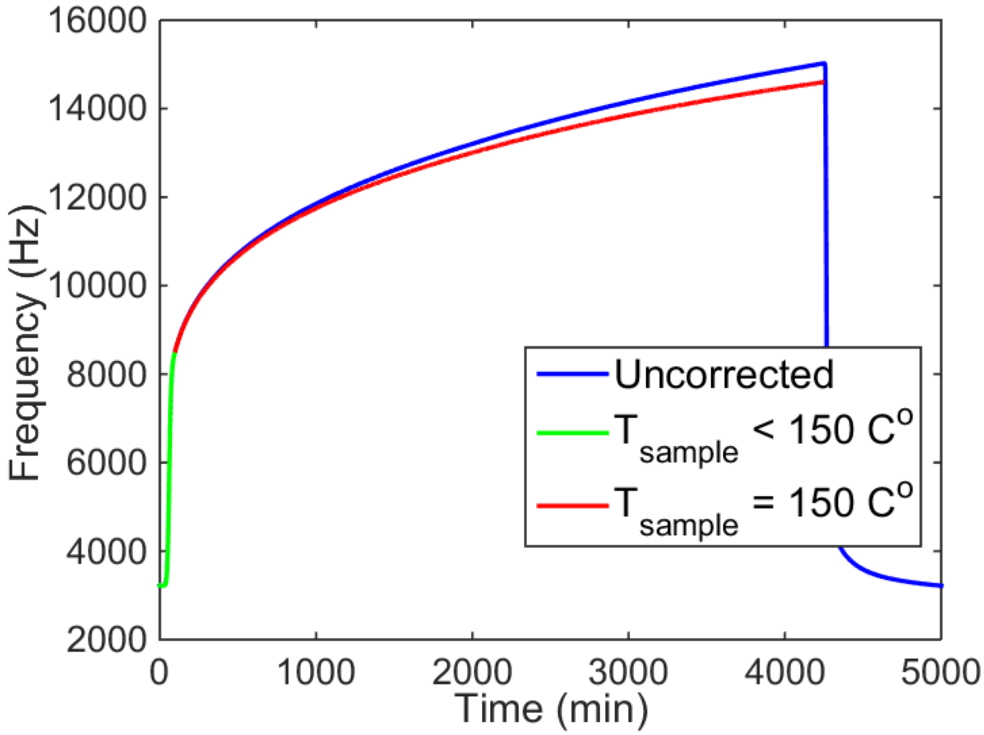

Figure 17: Raw data for TQCM for DC 93-500 sample 2.

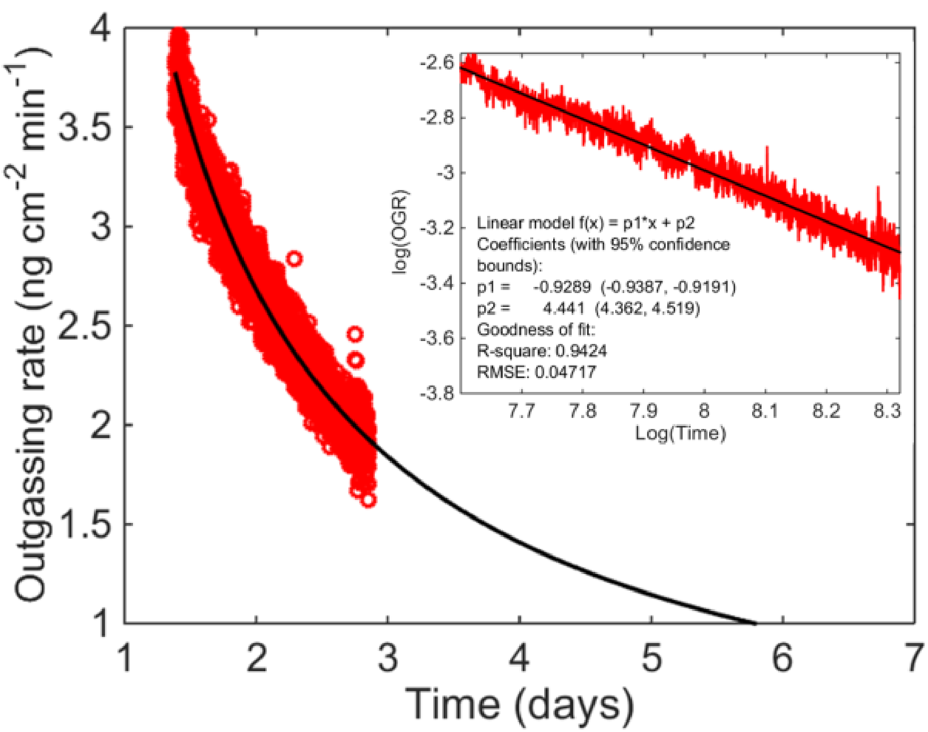

Figure 18: Outgassing rate as a function of time for sample 2. The insert shows the power law dependency of outgassing.

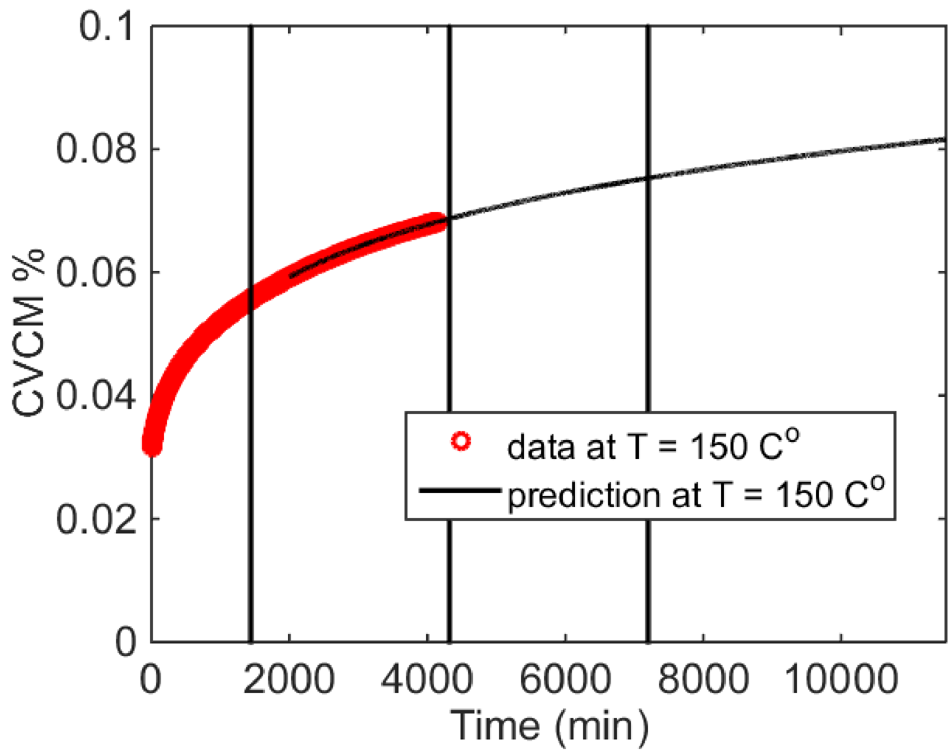

Figure 19: CVCM% from sample 2as a function of time

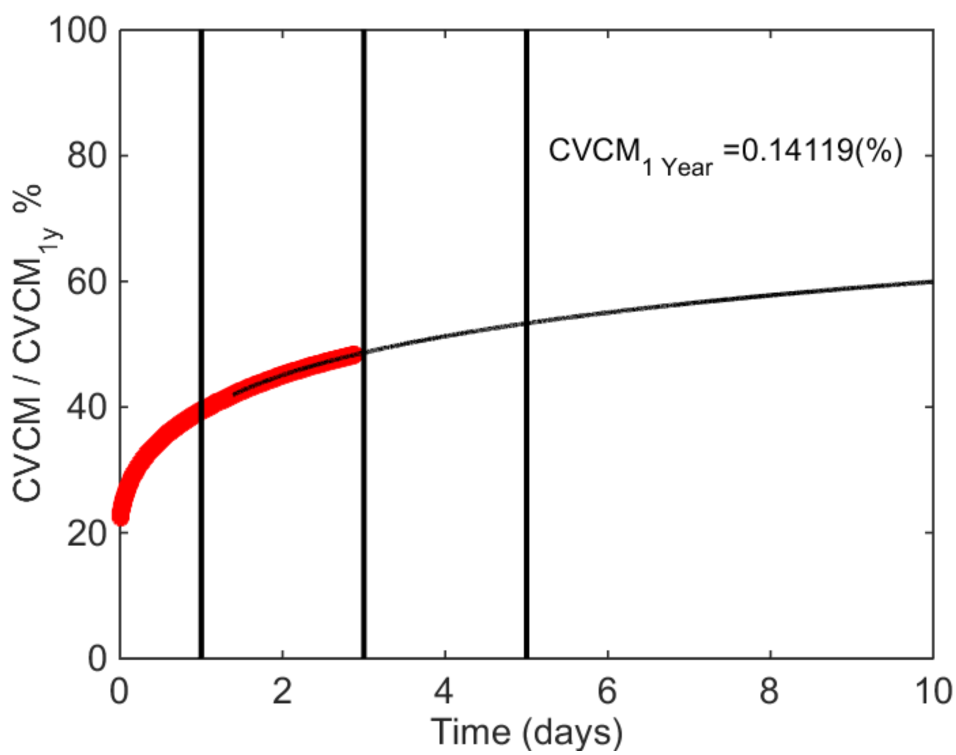

Figure 20: CVCM% for sample 2 graphed as a percentage of the expected CVCM in 1 year

Figure 21 and Figure 22 provide the CVCM% and the outgassing rate for the three samples. In Figure 21, the data for sample 7, DC 93-500 under a coverglass, shows almost no CVCM collected just by heating up the sample to 150 °C. The functional dependence of the outgassing rate is $t^{-0.6}$, which means that diffusion is the main mechanism driving the observed outgassing [1]. An extrapolation of the data for one year gives a CVCM of 0.09%.

The main question remains of how much CVCM would a bake-out eliminate in terms at an operational temperature of 70 °C or in the case of the Transformational Array at a higher temperature at Venus and a much lower temperature at 5 AU. In Option I, we intend to take outgassing rate data after thermal treatment at 150 °C and slowly lower the temperature of samples from 150 °C in small steps. At some temperature, the outgassing rate will no longer be measureable. The goal will be to measure or predict the CVCM at 70 °C or lower temperature using the functional dependence of the outgassing rate on time and temperature.

In terms of comparing the data from uncovered SCV2-2590 to uncovered DC 93-500, we observe a smaller CVCM for SCV2-2590 just by increasing the temperature of the sample to 150 °C. This is shown in Figure 21. The functional dependence of the OGR is $t^{-0.57}$. The data is suggesting a reduced contribution of the desorption component to the diffusion component for SCV2-2590 when compared to DC 93-500. Figure 23 shows the estimated CVCM in one year is 0.15%, which is comparable to the CVCM for DC 93-500. However, more contribution from diffusion seems to be captured in the estimation for SCV2-2590.

Our path forward in Option I is clearly defined based on the results in the Base Phase.

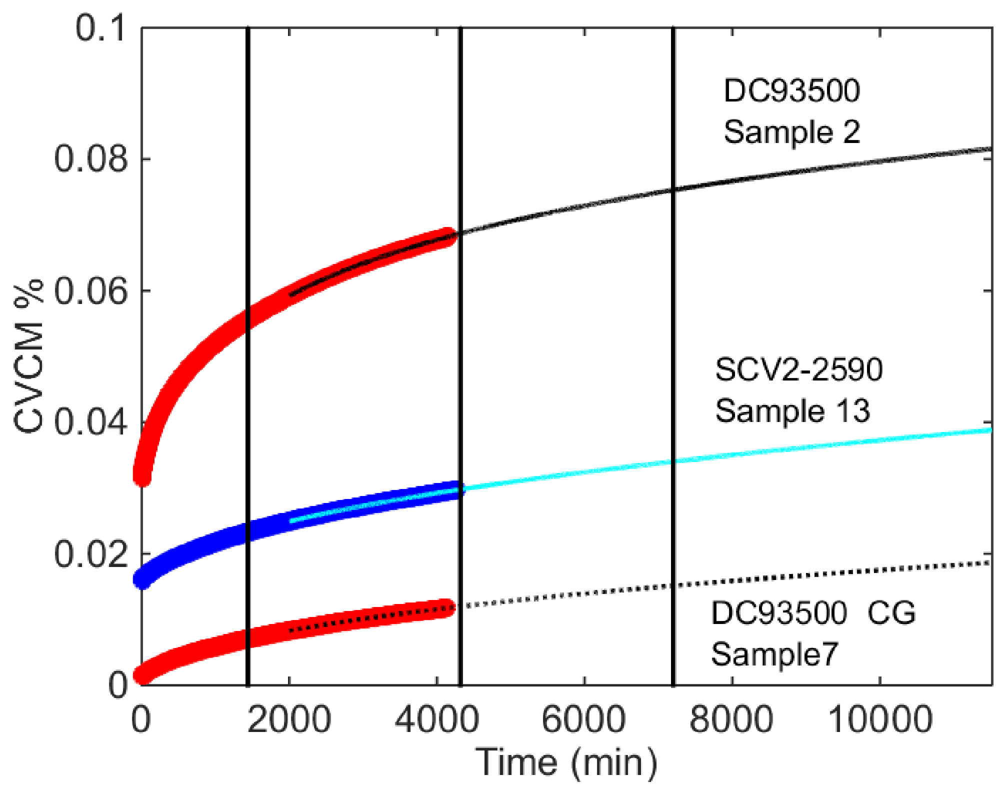

Figure 21: CVCM% for three different samples

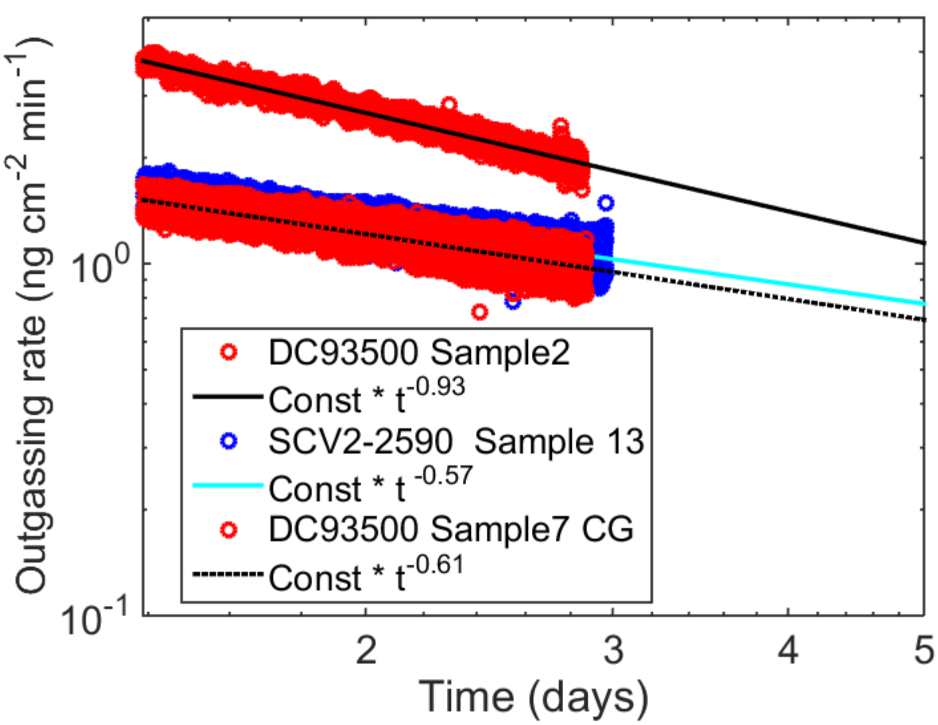

Figure 22: Outgassing rate for three different samples. The outgassing rate is much faster with the DC 93–500 than the other samples.

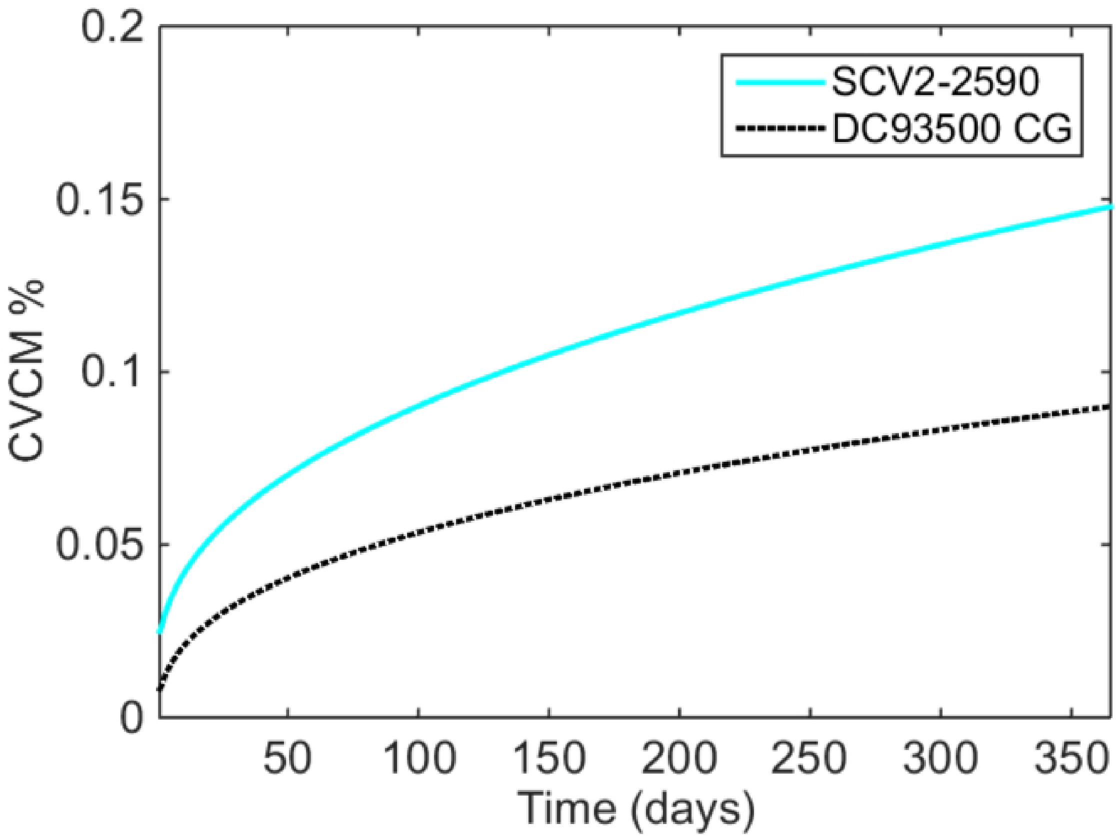

Figure 23: CVCM emitted as a function of time for SCV2-2590 and covered DC 93-500 extrapolated to one year

SolAero fabricated solar cell assemblies using adhesive loaded with microspheres. These were Mo-Sci precision glass spheres that are 125 μm in diameter. The spheres have an index of 1.47 compared to DC 93-500's index of 1.42. The samples with microspheres that were fabricated for outgassing tests appeared cloudy, which was an interesting discovery; and, thus it was thought that they might not transmit light as well as pure DC 93-500. So SolAero put it to the test. They manufactured three solar cell assemblies using 27.55 cm^2 ZTJ solar cells. The adhesive in the three assemblies each contained a different quantity of microspheres by volume: 0%, 33.3%, and 50%. All the samples were cured using the "standard" process: 70 °C for 60 minutes. Room temperature light I-V curves were taken at AM0 before and after glassing using a multi-zone simulator.

A picture of the samples is shown in Figure 24.

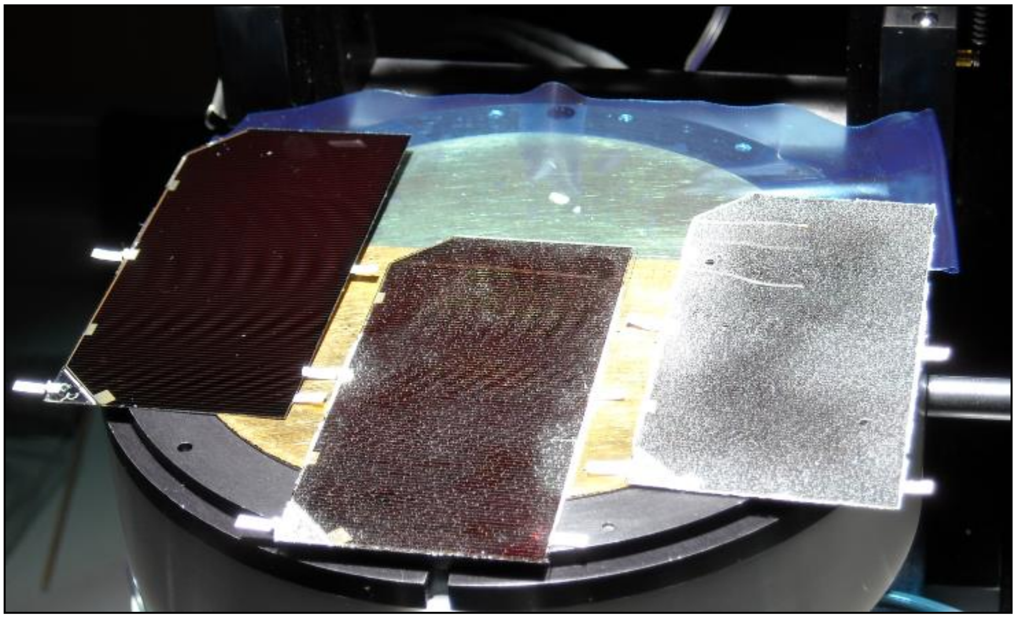

Figure 24: Solar cell assemblies with coverglass to cell adhesive having 0%, 33% and 50% microspheres by volume

Table I are some of the electrical results for the SCAs with adhesive filled spheres. This data shows that the Isc of the SCAs with 33% microsphere filled adhesive decreased 0.4% more than the SCAs with pure DC 93-500 adhesive on covering and that the SCAs with 50% microsphere filled adhesive decreased 5.1% more than the SCAs with pure DC 93-500. The 0.4% decrease might be satisfactory if the microspheres sufficiently decreased outgassing. The excess decrease in short circuit current may be a result of insufficient wetting of the microspheres by the adhesive. This could possibly be improved by using smaller microspheres.

Table I

Sample #	Cell ID	Cell Size (cm2)	Voc (V) Cell	Voc (V) CIC	Isc (mA) Cell	Isc (mA) CIC	Pmp (mW)	Pmp (mW) CIC
1 (0%)	234536-25B	27.55	2.660	2.625	**474.7**	**461.6**	1011	970.2
2 (33.3%)	234582-24A	27.55	2.678	2.642	**470.3**	**455.5**	1006	944.8
3 (50%)	234566-17B	27.55	2.658	2.615	**471.7**	**435.2**	995.9	894.9

Table II shows that mass of the cover to cell adhesive in the solar cell assemblies SolAero fabricated exceeded the adhesive used with no microspheres. This is counter to the motivation of using the spheres, which is to reduce the amount of adhesive that can outgas. SolAero believes this is because the microspheres used have a diameter of 125 μm and that this is not compatible with the desired adhesive thickness. Microspheres of a smaller diameter are available. In Option I, the samples with the smaller microspheres will be tested with the two goals to reduce the quantity of adhesive and to improve electrical performance.

Table II: SCA physical characteristics

Sample #	Microspheres % by Volume	Microspheres % by Mass	Total Mass (g)	Cell and CG Mass (g)	Mass of Adhesive + Microspheres (g)	Microsphere Only Mass (g)	Adhesive Only Mass (g)
1	**0**	0	3.164	3.036	0.128	0.000	**0.128**
2	**33.3**	50.5	3.600	2.968	0.632	0.319	**0.313**
3	**50**	67.1	4.254	2.951	1.303	0.874	**0.429**

Blanket work

Summary

The heat spreader used in previous versions of ROSA was successfully replaced with lighter weight stiffeners on the Transformational Array

Titanium was shown to be a successful mirror substrate and a blanket was fabricated with titanium mirror substrates. This will be delivered to NASA GRC.

A physical barrier to outgassing was fabricated and will be tested in Option I

DSS assembled an engineering model of the FACT configuration for the Transformational Array in the Base Phase that had been previously modeled in SolidWorks. This is shown in Figure 25. The model was fabricated to determine the effect of replacing the radiator, which is not required in LILT, with stiffeners.

Figure 25: Engineering model of the FACT configuration for the Transformational Array

The components were assembled using 3M 966-transfer adhesive. Assembly using the pressure sensitive adhesive (PSA) was straightforward and easier than using one or two part silicones. Stowing of the kick up springs does not overly torque the lateral stiffeners and is expected to function well when attached to a mesh back plane. The cell row acts as a shear plane in the assembly keeping the elements parallel. This FACT configuration (less the facetted radiator used in previous versions) is expected to roll-up nicely. DSS procured some 0.05-mm thick titanium foil and determined its bend characteristic during the fabrication of the radiators. FACT previously used stainless steel.

DSS identified a thermal formed Kapton shield at the cell edge as a method to minimize line of sight outgassing of DC 93-500 onto adjacent reflector assemblies and has manufactured two such assemblies; see Figure 26,
Figure 27, and Figure 28. This offers promise for further reductions of outgassing contaminants from the solar cell adhesives.

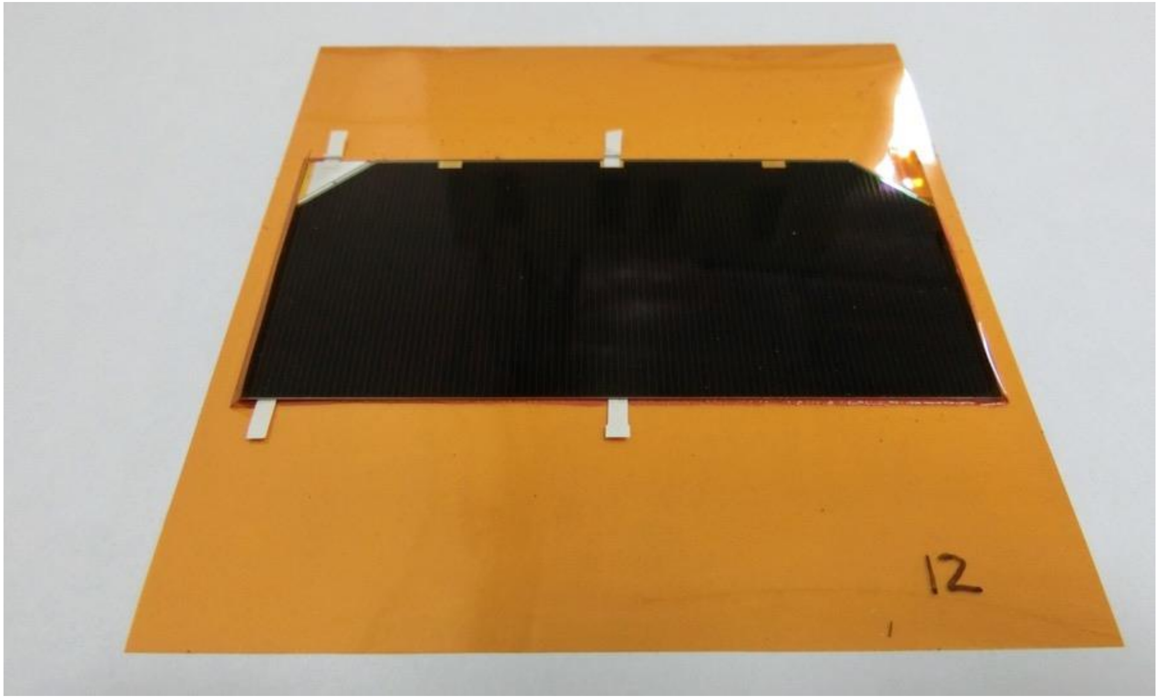

Figure 26: Thermoformed Kapton outgassing shield viewed from long side of cell.

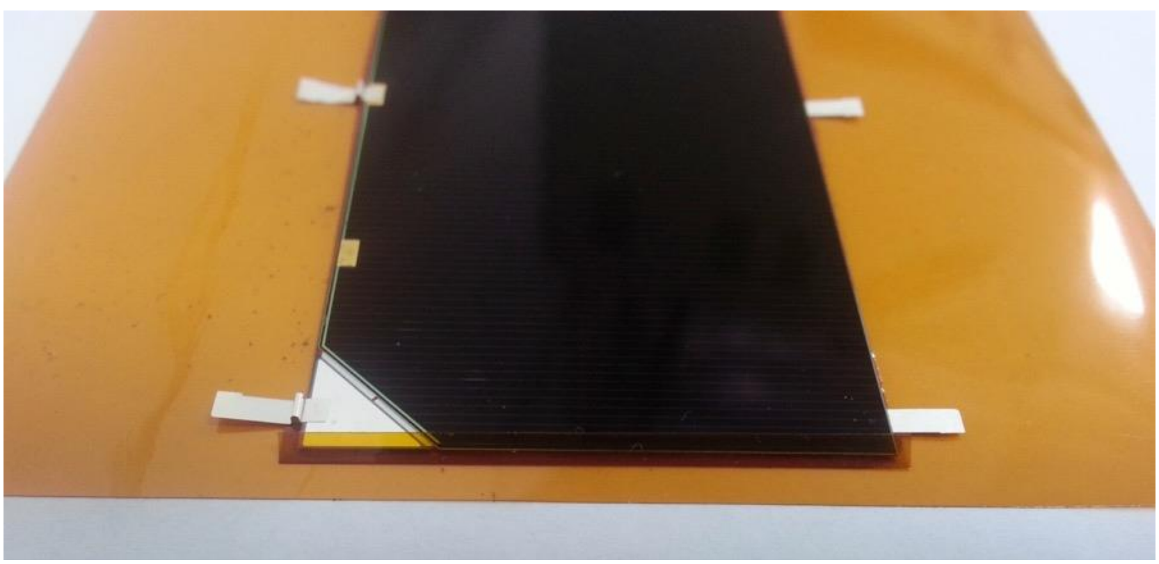

Figure 27: Thermoformed Kapton outgassing shield viewed from short side of cell.

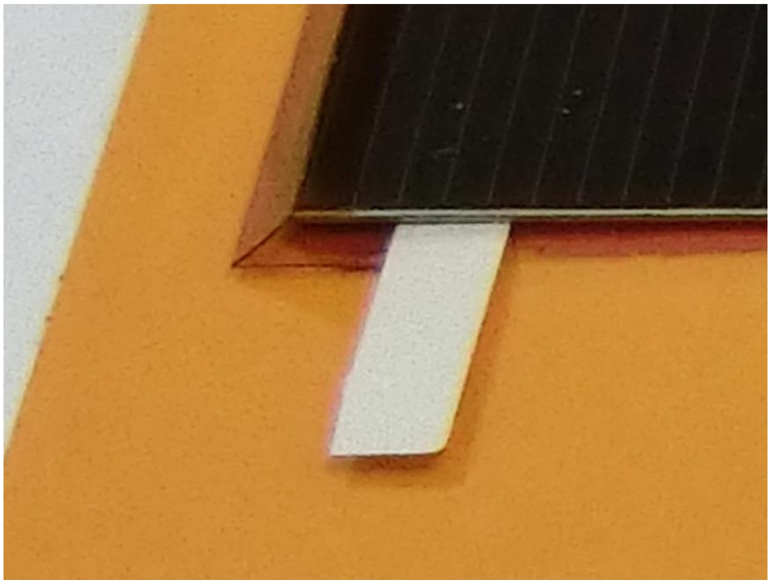

Figure 28: Close up of Thermoformed Kapton shield

DSS completed fabrication of a deliverable coupon, increasing the overall value of the funds expended in the Base Phase. While this coupon is not required under the contract, our intent is to deliver it to Glenn. Figure 29 is a photograph of the coupon. This coupon's mirror substrate differs from previous DSS coupons in that it uses titanium rather than stainless steel for the mirror substrates; which offers the benefit of magnetic cleanliness.

The coupon does not have a reflective coating. The work of coating the titanium and testing the coating for robustness during environmental exposures will be completed in Option I and Option II.

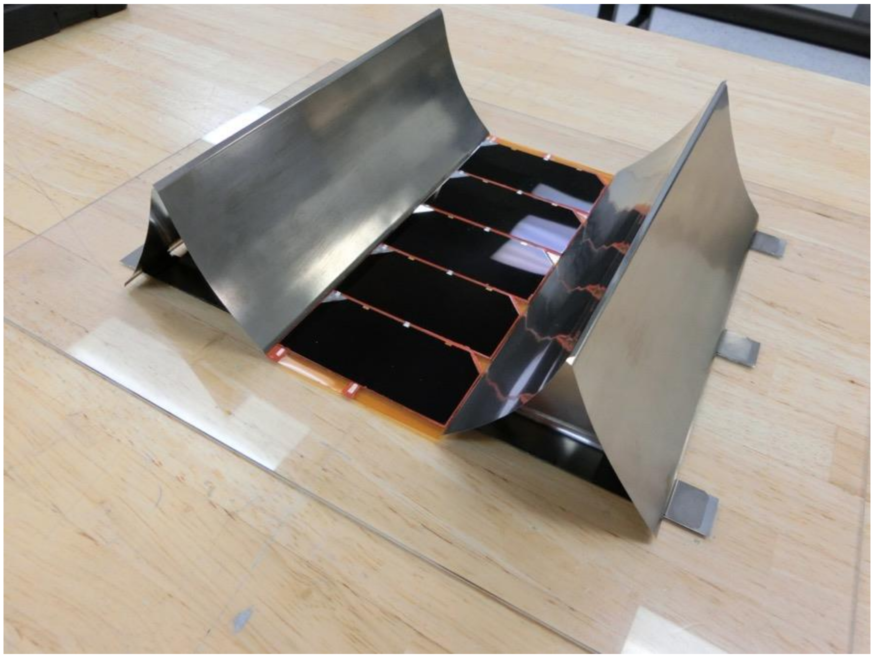

Figure 29: Coupon with uncoated mirrors

Other work

We have sent an abstract of our work to the 2017 Space Power Workshop for presentation at the conference in late April. The abstract was accepted. We look forward to sharing with the community the significant progress made in this technology approach towards the goals of the NRA.

Section II: Current Problems

Shunts were discovered in the Base Phase. These would affect overall solar cell production yield due to the loss of screened out parts. We have identified the cause of the shunts that degrade cell performance at LILT, which would currently be eliminated through screening. We have not eliminated the shunts. This does not affect TRL levels or Transformational Array performance, though it does cause an unnecessary expense that we believe can be reduced. In Option I, we intend to pursue process changes that will substantially reduce the number of shunted cells.

We made significant progress in evaluating outgassing products and comparison of different adhesives for low-outgassing adhesives for concentrator application; including the design of an effective Kapton shield. There is more work to be performed though this does not affect the TRL levels or meeting the Transformational Array goals as the array without concentrators is a viable option. Still, we want to reduce the array cost by using the concentrators. In Option I, we intend to pursue process changes that will practically eliminate outgassing as a cause of concentrator performance deterioration.

Section III: Risk Mitigation

Ten risks have been identified for the Option I and Option II work. They are listed after the following summary charts. The risks are against safety, cost, schedule and technical performance.

Table 1: Risk Matrix for Safety

Likelihood						
	Very High (5)					
	High (4)					
	Moderate (3)					
	Low (2)					
	Very Low (1)		5, 6, 9, 10	2, 3, 4		1, 7
	Risk 8, identified at the start of the Base Phase is retired	Minimal (1)	Minor (2)	Medium (3)	Major (4)	Very High (5)
		Consequence				

Table 2: Risk Matrix for Cost Performance

Likelihood						
	Very High (5)					
	High (4)					
	Moderate (3)					
	Low (2)					
	Very Low (1)				10	1, 2, 3, 4, 5, 6, 7, 9
	Risk 8, identified at the start of the Base Phase is retired	Minimal (1)	Minor (2)	Medium (3)	Major (4)	Very High (5)
		Consequence				

Table 3: Risk Matrix for Schedule Performance

Likelihood						
	Very High (5)					
	High (4)					
	Moderate (3)					
	Low (2)					
	Very Low (1)				10	1, 2, 3, 4, 5, 6, 7, 9
	Risk 8, identified at the start of the Base Phase is retired	Minimal (1)	Minor (2)	Medium (3)	Major (4)	Very High (5)
		Consequence				

Table 4: Risk Matrix for Technical Performance

Likelihood						
	Very High (5)					
	High (4)					
	Moderate (3)			1	6	
	Low (2)			2	3, 5, 7	
	Very Low (1)				4, 9, 10	
	Risk 8, identified at the start of the Base Phase is retired	Minimal (1)	Minor (2)	Medium (3)	Major (4)	Very High (5)
		Consequence				

Table 5: Threat Risk Consequence Criteria

Consequence	Personnel Safety	Asset Safety	Technical	Schedule	Cost
5 Very High	Death or permanent disability	Loss of flight system or critical asset; prevents mission success	Major impact to mission success; minimum mission success criteria not achievable	Irrecoverable impact to critical path; mission milestones cannot be met	≥ 15% of allocated budget -or- Unrecoverable, requiring outside funding to resolve
4 High	Severe (incapacitating) injury or illness	Major flight system or critical asset damage; impacts mission success	Significant threat to meeting primary mission objectives; minimum mission success criteria remain achievable	Major (≥ 2 weeks) impact to critical path or critical milestones, recoverable within total reserves and with workarounds -or- Major (≥ 4 weeks) impact to non-critical milestones; recoverable using workarounds without impact to critical path	≥ 10% but < 15% of allocated budget -or- Requires de-scope of significant capability or product
3 Medium	Emergency medical treatment for non-permanent injury	Minor flight system damage; repair, or replacement feasible. Moderate asset damage, no threat to mission success	No impact to primary mission objectives, and moderate impact to secondary mission objectives, requirements and technical margins. Minimum mission success criteria remain achievable with margin	Minor (≥2 weeks) impact to critical path or critical milestones, recoverable within minimum reserve profile -or- Moderate (≥ 4 weeks) impact to non-critical milestones; recoverable using workarounds and with only moderate impacts to successor milestones	≥ 5% but < 10% of allocated budget -or- Requires de-scope of secondary capability or product
2 Low	Minor first aid treatment	Negligible flight system damage. Minor asset damage.	No impact to primary mission objectives, and minor impact to secondary mission objective, requirements, and technical margins	No impact to critical path or critical milestones -or- Minor (< 4 weeks) impact to non-critical milestones; recoverable using workarounds and with minor impact to successor milestones	≥ 2% but < 5% of allocated budget -or- Requires significant change in effort with only minor impacts to products and deliverables
1 Very Low	No injury requiring treatment	No flight system or critical asset damage. Minor non-critical asset damage	No impact to full mission success criteria and negligible impact to requirements and technical margins	Negligible impact	≤ 2% of allocated budget -or- requires change in effort but no impact to products or deliverables

Table 6: Risk Likelihood Criteria

Likelihood	Safety (Likelihood of safety event occurrences)	Technical (Likelihood of not meeting mission technical requirements)	Cost/Schedule (Likelihood of not meeting allocated requirement or margin)
5 Very High *Nearly certain*	$P_S > 0.1$	> 60%	>75%
4 High *Highly likely*	$0.01 < P_S \leq 0.1$	$35\% < P_T \leq 60\%$	$50\% < P_{CS} \leq 75\%$
3 Moderate *May occur*	$0.001 < P_S \leq 0.01$	$15\% < P_T \leq 35\%$	$25\% < P_{CS} \leq 50\%$
2 Low *Not likely*	$10^{-5} < P_S \leq 0.001$	$2\% < P_T \leq 15\%$	$5\% < P_{CS} \leq 25\%$
1 Very Low *Very unlikely*	$P_S \leq 10^{-5}$	$0.1\% < P_T \leq 2\%$	$P_{CS} \leq 5\%$

In the following risk evaluations, the safety risk consequence is evaluated with tasks and activities that are directly and uniquely associated with the risk. For example, the risk consequence never includes certain ancillary activities such as transportation of test articles in automobiles travelling at highway speeds, which would always have a safety risk consequence of 5.

All risks are evaluated with respect to the contract being executed as opposed to the flight of a Transformational Array.

The cost risk requires special elaboration. It is evaluated with respect to the cost of this contract. However, some of the risks listed below do not affect the technical performance of a production Transformational Array but would affect its cost. These risks are put into the Technical Risk category for this contract but not the cost risk as these risks do not affect this contract cost but do affect a goal of the contract - - namely to keep the cost of a production Transformational Array low.

ID 1: IMM solar cells do not meet the power requirements at BOL

Risk Statement: If the IMM cells do not meet or come close to meeting power requirements at beginning of life, it will be difficult or impossible to meet several goals of the contract including cell efficiency at 47%, blanket efficiency of 32%, areal power density of 8 W kg^{-1}, and packing density of 66 kW m^{-3}. This will deplete cost and schedule reserves and if persistent will prevent us from meeting contract goal requirements. The technical consequence of this occurring is lowered from a 4 to a 3 as a result of the discovery in the Base Phase that the IMM solar cells are lighter than assumed at the beginning of the Base Phase. The likelihood of the risk has been increased to a 3 because the Base Phase efficiencies were not as high as hoped.

Risk Context: The context of the risk is the history of increasing solar cell efficiency over the years and the history of the production of gallium arsenide based solar cells.

Likelihood and Consequence to Safety: 1, 5. The likelihood of this risk is based on the safety record of developing and producing Gallium Arsenide based solar cells; and the safety monitoring and interlocks that are in place. SolAero has gone over 5.5 years without an injury related to cell manufacture. (The record of safety goes back further than that, but a report for earlier was not available for this document.) The consequence is based on the toxicity of the materials used in the production of the cells. A leak in a reactor could be deadly.

Likelihood and Consequence to Cost: 1, 5. The rationale for this is that APL will trade the cost risk to the technical risk. Essentially, we will accept whatever cell efficiency is obtained for the planned cost. If we do not do this the consequence could be exceeding budget by more than 15%; and, hence is a 5.

Likelihood and Consequence of to Schedule Performance: 1, 5. The rationale for this is that APL will trade the schedule risk to the technical risk. Essentially, we will accept whatever cell efficiency is obtained for the planned schedule. If we do not do this the consequence could be exceeding schedule for several years.

Likelihood and Consequence to Technical Performance: 3, 3. The likelihood of meeting cell efficiency is difficult to determine because the required cells have not been fabricated. However, it is analytically known that the cell efficiency is achievable with available materials and with methods of fabrication that are generally known to be practicable, so calling it a 3. The consequence of not meeting power requirement will be that the Transformational Array will fall short of meeting three of the four efficiency related goals (having already achieved one). We are already at 96% of the BOL efficiency goal, 101% of the end of life blanket efficiency goal, 95% of the specific power goal and 86% of the packaging efficiency goal. We believe this rationale assesses to a level 3 consequence.

Risk Status: Evaluated at the end of the Base Phase; still a risk.

Timeframe: This risk will be present through the start of the contract until the approximately the last 4 months at which time it's status will be defined.

Mitigation Plan: We are placing substantial resources into developing IMM solar cells that meet the power requirements. If during the execution of Option I and Option II, it becomes apparent that the efficiency is not increasing as required, we will devote resources to further reducing the mass of the array, which will have a similar effect to increasing the IMM cell efficiency. Depending on the assessment at the time, we will, with the concurrence of Glenn, increase resources to the development of the cell at the expense of other development. This mitigation plan will be in place for the interval from May, 2017 until four months prior to the end of Option II.

ID 2: IMM solar cells do not meet the power requirements after exposure to 4E15 1 MeV electrons

Risk Statement: If the IMM cells do not meet power requirements at end of life, it will be difficult to meet two end of life goals of the contract: over 28% blanket efficiency and over 10 W kg^{-1} specific power. The consequence of this occurring is lowered from a 4 to a 3 as a result of the discovery in the Base Phase that the IMM solar cells are lighter than assumed at the beginning of the Base Phase.

Risk Context: The context of the risk is the history of determining solar cell radiation degradation under charged particle radiation over the past twenty years.

Likelihood and Consequence to Safety: 1, 3. The likelihood of this risk is based on the safety record of exposing solar cells to radiation. The consequence is based on the consequences of exposure to irradiated solar cells that have not been sufficiently “cooled.” The consequence could also be increased to a 5 due to the possibility of increasing the chances of a life ending cancer. We think the 3 is more likely; but it is a judgment call.

Likelihood and Consequence to Cost: 1, 5. The rationale for this is that APL will trade the cost risk to the technical risk. Essentially, we will accept whatever cell performance after exposure to charge particles that we obtain for the planned cost. If we do not do this the consequence could be exceeding budget by more than 15% due to iterations of designing and re-testing cells; and, hence is a 5.

Likelihood and Consequence of to Schedule Performance: 1, 5. The rationale for this is that APL will trade the schedule risk to the technical risk. Essentially, we will accept whatever cell performance is obtained for the planned schedule. If we do not do this the consequence could be exceeding schedule for several years.

Likelihood and Consequence to Technical Performance: 2, 3 - This could happen as these cells are not yet manufactured or tested to 4E15 1 MeV electrons. The likelihood is reduced from 3 to 2 due to comprehensive radiation exposure data now available on IMM+ cells.

Risk Status: Evaluated at the end of the Base Phase; still a risk.

Timeframe: This risk will be present through the start of the contract until the approximately the last 4 months at which time it’s status will be defined.

Mitigation Plan: As very high efficiency IMM solar cells are required to meet the NRA goals, we are placing substantial resources into developing IMM solar cells that meet the power requirements after exposure to charged particle radiation. If during the execution of Option I and Option II, it becomes apparent that the resistance to charged particle radiation is not as required, we will devote resources to further reducing the mass of the array, which will have a similar effect to increasing the IMM cell efficiency after exposure to charged particle radiation. Depending on the assessment at the time, we with the concurrence of Glenn may also increase resources to the development of cell radiation resistance at the expense of other development. This mitigation plan will be in place from the start of the contract until four months prior to the end of Option II.

ID 3: IMM solar cells will not meet the power requirements after exposure to thermal vacuum cycling, xenon plasma, or electrostatic discharge (or may just plain not meet power requirements).

Risk Statement: If the IMM cells do not meet power requirements at end of life due to failure after exposure to an environment, it will be difficult or impossible to meet four end of life goals of the contract: over 28% blanket efficiency, over 10 W kg^{-1} specific power, operation in a plasma generated by xenon thrusters and capability to operate at over 300 V.

Risk Context: The context of the risk is the history of testing IMM+ solar cells in similar environments.

Likelihood and Consequence to Safety: 1, 3. The likelihood of this risk is based on the author's informal estimation of the safety record of exposing solar cells and arrays to the listed environments. The consequence is based on the possibility of such as receiving a shock in the test of the articles.

Likelihood and Consequence to Cost: 1, 5. The rationale for this is that APL will trade the cost risk to the technical risk. Essentially, we will accept whatever cell performance obtains after exposure to the listed environments that we achieve for the planned cost. If we do not do this the consequence could be exceeding budget by more than 15% due to iterations of designing and re-testing array technology; and, hence is a 5.

Likelihood and Consequence of to Schedule Performance: 1, 5. The rationale for this is that APL will trade the schedule risk to the technical risk. Essentially, we will accept whatever cell performance obtains for the planned schedule. If we do not do this the consequence could be exceeding schedule for several years due to repeated iterations of array tests.

Technical Likelihood and Consequence: 2, 4 **-** This could occur as IMM cells are not yet manufactured or tested to these environments. However, the performance of IMM cells in some of these environments and the performance of ZTJ cells in the environments suggest that the needed IMM cells will not have an issue.

Risk Status: Evaluated at the end of the Base Phase; still a risk.

Timeframe: This risk will be present through the start of the contract until the end of Option I.

Mitigation Plan: The following mitigations will be employed to address this risk.

1. Some mitigation has already been achieved against this risk. SolAero has fabricated IMMX+ solar cells, thermal vacuum cycled them, and exposed them to hard particle radiation. They performed as expected. The slight deficiency to this work is that the IMM+ cells are not identical to the IMM solar cells that the Extreme Environment array requires. Nonetheless, this provides an indication that at least the five junction cells required by the Transformational Array can be fabricated and successfully perform after exposure to thermal vacuum cycling.
2. IMM cells were produced during the base phase of the contract and will be tested during the Option 1 phase of the contract. These cells will provide

more data reducing the risk to the performance of the IMM cells needed in Option II.
3. APL will devote substantial resources to mitigating this risk.

ID 4: The blanket or associated parts will fail after exposure to thermal vacuum cycling, xenon plasma, or electrostatic discharge.

Risk Statement: If the blanket parts fail after exposure to a test environment, it will be difficult or impossible to meet four end of life goals of the contract: over 28% blanket efficiency, over 10 W kg^{-1} specific power, operation in a plasma generated by xenon thrusters and capability to operate at over 300 V.

Risk Context: The context of the risk is the history of testing the ROSA blankets and other components under similar environments.

Likelihood and Consequence to Safety: 1, 3. The likelihood of this risk is based on the author's informal estimation of the safety record of exposing solar arrays to the listed environments. The consequence is based on the possibility of such as receiving an electric shock in the test of the articles.

Likelihood and Consequence to Cost: 1, 5. The rationale for this is that APL will trade the cost risk to the technical risk. Essentially, we will accept whatever array performance obtains after exposure to the listed environments that we achieve for the planned cost. If we do not do this the consequence could be exceeding budget by more than 15% due to iterations of designing and re-testing array technology; and, hence is a 5.

Likelihood and Consequence of to Schedule Performance: 1, 5. The rationale for this is that APL will trade the schedule risk to the technical risk. Essentially, we will accept whatever array performance obtains for the planned schedule. If we do not do this the consequence could be exceeding schedule for several years due to repeated iterations of array tests.

Technical Likelihood and Consequence: 1, 4 **-** This could occur as some parts are not yet manufactured or tested to these environments. However, the performance of ROSA arrays and the similarity of the vast majority of these parts to the parts in the Transformational array suggest that there will not be an issue.

Risk Status: Evaluated at the end of the Base Phase; still a risk.

Timeframe: This risk will be present through the start of the contract until four months prior to the end of Option II.

Mitigation Plan: Care will be taken to design components close to designs that have already successfully passed exposures to the required environments.

ID 5: Fail to reduce outgassing to an acceptable level for use with concentrators

Risk Statement: If the outgassing is not reduced to an acceptable level, the vast majority of the negative impact will be on cost. This is because the technical performance metrics of the Transformational Array are only slightly reduced if concentrators are not used.

Risk Context: The context of the risk is the history of the poor in-flight performance of reflective concentrator arrays.

Likelihood and Consequence to Safety: 1, 2. The tests to develop low outgassing arrays are generally safe and the consequences of a poorly conducted tests are minimal. Basically, the adhesives are safe to handle and the equipment for the testing is forgiving.

Likelihood and Consequence to Cost: 1, 5. The rationale for this is that APL will trade the cost risk to the technical risk. Essentially, we will accept whatever outgassing is obtained for the planned cost. If we do not do this the consequence could be exceeding budget by more than 15%; and, hence is a 5.

Likelihood and Consequence of to Schedule Performance: 1, 5. The rationale for this is that APL will trade the schedule risk to the technical risk. Essentially, we will accept whatever outgassing is obtained for the planned schedule. If we do not do this the consequence could be exceeding schedule for several years.

Likelihood and Consequence to Technical Performance: 2, 4. There are several possible ways to reduce outgassing and these seem like they have a reasonable chance of success. Therefore, there is a low likelihood of failure. The technical consequences of failure to the technical goals is low because the Transformational Array can perform quite well without the concentrators. However, the cost goal would be adversely affected, hence the consequence of 4.

Risk Status: Evaluated at the end of the Base Phase; still a risk.

Timeframe: This risk will be present through the start of the contract until the end of Option I.

Mitigation Plan: Significant resources are being applied to reduce this risk.

ID 6: Fail to eliminate mirror coating delamination

Risk Statement: If the risk to obtaining a reliable coating is not reduced to an acceptable level, the vast majority of the negative impact will be on cost. This is because the technical performance metrics of the Transformational Array are only slightly reduced if concentrators are not used.

Risk Context: The context of the risk is the history of delamination of the mirror coatings on previous FACT work.

Likelihood and Consequence to Safety: 1, 2. The tests needed to develop mirror coatings are generally safe and the consequences of a poorly conducted tests are minimal. Basically, the equipment to coat is safe and the equipment for the testing is forgiving.

Likelihood and Consequence to Cost: 1, 5. The rationale for this is that APL will trade the cost risk to the technical risk. Essentially, we will accept whatever delamination is obtained for the planned cost. If we do not do this the consequence could be exceeding budget by more than 15%; and, hence is a 5.

Likelihood and Consequence of to Schedule Performance: 1, 5. The rationale for this is that APL will trade the schedule risk to the technical risk. Essentially, we will accept whatever delamination is obtained for the planned schedule. If we do not do this the consequence could be exceeding schedule for several years.

Likelihood and Consequence to Technical Performance: 3, 4. APL technical experts believe that reliably adhering the coating to the mirrors is tricky but that it is possible. The technical consequence is low because the array can perform well without the concentrators. However, the consequence to the cost goal is relatively high, hence the 4.

Risk Status: Evaluated at the end of the Base Phase; still a risk.

Timeframe: This risk will be present through the start of the contract until the end of Option I at which time the outgassing work will be stopped.

Mitigation Plan: Significant resources are being applied to reduce this risk.

ID 7: Fail to eliminate cell shunts

Risk Statement: If we do not eliminate the shunts, the Transformational Array will still meet all of the formally defined specific technical contract goals. If there are no production controls to prevent or at least keep the percentage of shunted cells at an acceptable level, this increases the potential of an undefined cost risk increase.

Risk Context: Shunts were discovered to be an issue at LILT during the execution of the Base Phase.

Likelihood and Consequence to Safety: 1, 5. The likelihood of this risk is based on the safety record of developing and producing Gallium Arsenide based solar cells;
Likelihood and Consequence to Safety: 1, 5. The likelihood of this risk is based on the safety record of developing and producing Gallium Arsenide based solar cells;

and the safety monitoring and interlocks that are in place. SolAero has gone over 5.5 years without an injury related to cell manufacture. (The record of safety goes back further than that, but a report for earlier was not available for this report.) So, the likelihood is evaluated to be 1. The consequence is based on the toxicity of the materials used in the production of the cells. A leak in a reactor could be deadly.

Likelihood and Consequence to Cost: 1, 5. The rationale for this is that APL will trade the cost risk to the technical risk. Essentially, we will accept whatever shunts are obtained for the planned cost. If we do not do this the consequence could be exceeding budget by more than 15%; and, hence is a 5.

Likelihood and Consequence of to Schedule Performance: 1, 5. The rationale for this is that APL will trade the schedule risk to the technical risk. Essentially, we will accept whatever shunts are obtained for the planned schedule. If we do not do this the consequence could be exceeding schedule for several years.

Likelihood and Consequence to Technical Performance: 2, 4. SolAero has identified the cause of the shunts and it believes that there is a good probability of eliminating them. The technical consequence to the array is small because the cells with shunts can be discarded. However, the cost impact is substantial, hence the consequence of 4.

Risk Status: Evaluated at the end of the Base Phase, this risk replaced the risk associated with flat spots. The flat spot risk was retired because none were found in the Base Phase work.

Timeframe: This risk will be present through the start of the contract until four months from the end of Option II, when this work will be completed.

Mitigation: APL and SolAero are applying substantial resources to eliminating the shunts. At the beginning of the base phase this risk was related to flat spots. The likelihood of fixing the problem has increased somewhat as SolAero knows the cause of the shunts and has fixed similar issues on heritage cells.

ID 8: IMM solar cells cannot be formed into CICS or interconnected. This risk is retired as of the end of the Base Phase.

APL has retired this risk as its likelihood has dropped to the same level of risk that is inherent to the formation of CICS and strings using state of the art cells.

Risk Status: Evaluated at the end of the Base Phase and found not to be a risk worth formally reporting.

ID 9: The ROSA array deployment mechanisms and structure will not attain goal mass

Statement: If this risk manifests, the goals for an array power density of 8 W kg^{-1} and packing density of 66 kW m^{-3} may be slightly exceeded or reserves decreased.

Context: This risk is related to recent work performed on ROSA arrays prior to the Transformational Array.

Likelihood and Consequence to Safety: 1, 2. It is unlikely that anything associated with this work will be unsafe; and if anything did happen the consequence would be slight. Perhaps a finger could be injured during the course of testing the deployment mechanisms.

Likelihood and Consequence to Cost: 1, 5. The rationale for this is that APL will trade the cost risk to the technical risk. Essentially, we will accept whatever ROSA performance are obtained for the planned cost. If we do not do this the consequence could be exceeding budget by more than 15%; and, hence is a 5.

Likelihood and Consequence of to Schedule Performance: 1, 5. The rationale for this is that APL will trade the schedule risk to the technical risk. Essentially, we will accept whatever ROSA performance is obtained for the planned schedule. If we do not do this the consequence could be exceeding schedule for several years.

Likelihood and Consequence to Technical Performance: 1, 4 This is not likely as DSS has sufficient experience with the ROSA mechanisms and structure to make accurate mass estimates. Still we are pushing mass to the lowest possible limits. The likelihood of this occurring has dropped from 2 to 1 at the end of the base phase due to replacement of the heat spreader by a much lighter stiffener. The consequence could be as high as 4.

Risk Status: This risk remains at the end of the Base Phase.

Timeframe: This risk will be present through the start of the contract until four months from the end of Option II, when this work will be completed.

Mitigation: APL and SolAero are applying adequate resources to address this risk.

ID 10: The ROSA array will not deploy

Statement: If this risk manifests, we would not meet contract goals.

Context: This risk is in the context of previous ROSA and previous performance of other types of array. Any failure to deploy would likely be easy to fix.

Likelihood and Consequence to Safety: 1, 2. It is unlikely that anything associated with this work will be unsafe; and if anything did happen the consequence would be slight. Perhaps a finger could be injured during the course of testing the deployment mechanisms.

Likelihood and Consequence to Cost: 1, 4. The rationale for this is that APL will trade the cost risk to the technical risk. Essentially, we will accept whatever ROSA deployment performance is obtained for the planned cost. If we do not do this the consequence could exceed budget.

Likelihood and Consequence of to Schedule Performance: 1, 4. The rationale for this is that APL will trade the schedule risk to the technical risk. Essentially, we will accept whatever ROSA performance is obtained for the planned schedule. If we do not do this the consequence could be exceeding schedule.

Likelihood and Consequence to Technical Performance: 1, 4 This is not likely as DSS has sufficient experience with the ROSA to be certain that it will deploy. This risk is included because array deployment has been a prominent failure mechanism for flight arrays. A failure to deploy in test would be serious to the contract goals as it would mean work would have to be completed to make the technology function properly.

Risk Status: This risk remains at the end of the Base Phase.

Timeframe: This risk will be present through the start of the contract until four months from the end of Option II, when this work will be completed.

Mitigation: APL and SolAero are applying adequate resources to address this risk.

Section IV: Work Planned

The following Option I work is planned:

- 35% BOL goal
    - Eliminate shunts in IMM solar cells
    - Optimize IMM solar cells for LILT operation
    - Fabricate sample IMM cells and test at LILT to be sure harmful LILT phenomenon are cured
- 28 % Blanket goal
    - Test sample of IMM cells under end of life conditions:
      50 W m^{-2}, -125 °C, and 4E15 1 MeV e cm^{-2}
    - Test adhesives and adhesive treatments to eliminate outgassing on the mirrors
    - Test coverglass to cell adhesives to be sure they will not darken in concentrator operation
    - Refine concentrator coating, eliminate delamination

    - Evaluate ultra-low outgassing adhesive for the back of the wing
    - Manufacture two 150 mm x 150 mm blankets with back-wiring and ultra-low outgassing cell to substrate adhesive
    - Estimate array mass and performance at BOL
    - Functionally test and expose a blanket to environments
    - Evaluate array performance: update models, assess performance, assess TRL, and assess blanket efficiency at EOL.
- Analyze Option I technology against the 8 - 10 W kg^{-1} goal
- Analyze Option I technology against a packaging density of > 60 W m^{-3}
- Test for blanket damage in a Xenon Plasma at GRC
- Demonstrate that the array can withstand stowage and launch
- Analyze technology against operation at >300 V.
- Analyze technology against damage in a Xenon plasma
- Design technology for compatibility with magnetic and electrical cleanliness.
- Plan a production for reduced costs and cell inspection

Section V: Analysis

Summary

The specific power of a 25 kW Transformational Array at 28 °C and AM0 is 225 W kg^{-1}

The specific power of a 25 kW Transformational Array at LILT 10.2 W kg^{-1}

The stowed power density is 51.4 kW m^{-3}

The following analysis assumes the use of technology and data that is available at the end of the Base Phase. SolAero produced IMM cells of higher efficiency during the Base Phase of the project, 33.7% at standard conditions, than the 32% efficient cells used in this analysis. The less efficient cells were used because more was known about their temperature coefficients and their performance after irradiation.

IMMX+ cell performance data and temperature coefficients, shown in Table 7, Table 8, Table 9 and Table 10 are used in this analysis.

Table 7: Electrical IMMX+ Output Parameters at Air Mass Zero at 28 °C

BOL Efficiency	32.0%
Voc (V)	4.78
Isc (mA cm^{-2})	10.66
Vmp (V)	4.28
Jmp (mA cm^{-2})	10.12

Table 8: Electrical Degradation After Exposure to 1 MeV Irradiation with No Anneal

Fluence (e cm^{-2})	Voc	Isc	Vmp	Jmp	Pmp
5E14	0.914	0.987	0.915	0.981	0.898
1E15	0.892	0.966	0.882	0.967	0.853
5E15	0.83	0.87	0.835	0.835	0.697

Table 9: Electrical Degradation after Exposure to 1 MeV Irradiation with Anneal

Fluence (e cm^{-2})	Voc (V)	Isc (A)	Vmp (V)	Jmp (A)	Pmp (W)
5E14	0.923	0.987	0.927	0.982	0.910
1E15	0.900	0.966	0.890	0.977	0.870
5E15	0.841	0.874	0.840	0.848	0.712

Table 10: Temperature Coefficients

Fluence (e cm^{-2})	Voc (mV °C^{-1})	Isc (μA cm^{-2} °C^{-1})	Vmp (mV °C^{-1})	Jmp (μA cm^{-2} °C^{-1})
BOL	-9.0	9.8	-9.3	6.7
5E14	-9.6	9.9	-10.2	5.2
1E15	-9.8	9.7	-10.2	3.3
5E15	-10.7	9.0	-9.9	7.6

For the Transformational Array, the FACT standard power module (SPM) is used. It consists of three 10-cell IMMX+ strings with adjacent titanium substrate reflectors that concentrate sunlight on the solar cell string. The concentrator assembly reduces the number of solar cells of the targeted solar array and greatly reduces the cost of the solar array. The solar array blanket consists of an open-weave fiberglass mesh backplane that is tiled with the FACT standard power module. The unique titanium reflectors can be stowed flat and the blanket rolled during stowage of the ROSA solar array. The silver coated reflectors provide a high reflective efficiency with the following performance characteristics:

- 2.007 increase in Imp
- 0.995 decrease in Vmp
- 1.991 increase in Isc
- 1.022 increase in Voc
- 1.9998 increase in Pmp

The mass of the FACT SPM includes all components used in the assembly including adhesives. The SPM specific power at 28 °C is calculated to be 452 W kg^{-1} and exceeds the performance of a fully populated SPM without reflectors due to the low mass of the metal foil components. Table 11 displays the mass of the FACT components.

Table 11: Mass of FACT Concentrator SPM Components

Item	Quantity	Unit Mass (g)	Mass (g)
Aluminum Radiator	0	25.865	0
Kapton Insulator	3	1.186	3.503
Kapton Insulator/Radiator Bond (0.072 mm)	3	0.566	1.699
IMM Cell Assembly	30	2.365	70.960
Foam strip with 0.102 mm bond	6	0.572	3.432
FACT reflector (0.508 mm thick)	6	7.128	42.767
Titanium Cross Stiffener (0.508 mm thick)	4	1.698	6.792
Kick-up Spring	14	1.258	17.619
Spring Adhesive Bond	16	0.067	1.071
Kapton Spot Bond with Adhesive for mesh	16	0.111	1.799
FACT SPM Total Mass			149.62

Table 12 reports the performance summary data for the FACT SPM.

Table 12: FACT Concentrator SPM Summary Data

Reflector Efficiency	0.955
Concentrator Ratio	2.013
SPM Power (W)	67.63
SPM Specific Power (W kg^{-1})	452

DSS performed a full power analysis to determine the BOL string output at the SADA-spacecraft connector. The analysis included the following loss factors:

- LAPSS calibration to AM0
- CIC assembly voltage loss
- UV degradation
- Micro-meteoroid and debris damage
- Loss due to contamination
- Cell current miss-match
- Blocking diode voltage loss
- Wing harness voltage loss

The estimated power output of the FACT SPM at the spacecraft connector is 67.54 W.

Table 13: FACT SPM Performance Calculation

BOL 1 AU Power Analysis -32.0% IMM PV - Unconcentrated vs. FACT Concentrator														
			Unconcentrated Planar Panel						FACT Concentrator Panel (2.1X)					
	Reference Value	Loss Factor	Isc	Imp	Vmp	Voc	Pmp	System Efficiency	Isc	Imp	Vmp	Voc	Pmp	System Efficiency
Bare Cell @ 28°C			0.294	0.279	4.280	4.780	1.194	32.01%	0.585	0.560	4.262	4.886	2.386	31.83%
LAPSS Calibration to AM0		0.990	0.291	0.276					0.579	0.554				
CIC Assembly Voltage Loss		0.995			4.259	4.756					4.240	4.862		
CIC Glassing/Assembly Current Loss		0.995	0.289	0.275					0.576	0.551				
Sun Distance (Aphelion Solstice)	1.0000 AU	1.000	0.289	0.275					0.576	0.551				
Alpha Off-Pointing	0.00 deg	1.000	0.289	0.275					0.576	0.551				
Beta Off Pointing	0.00 deg	1.000	0.289	0.275					0.576	0.551				
UV degradation		0.990	0.286	0.272					0.570	0.546				
Micro-Meteoroid and Debris		0.990	0.284	0.269					0.565	0.540				
Contamination		0.990	0.281	0.267					0.559	0.535				
Thermal Cycle Current Loss		1.000	0.281	0.267					0.559	0.535				
Thermal Cycle Voltage Loss		1.000			4.259	4.756					4.240	4.862		
Isc Radiation Degradation	BOL assumed	1.000	0.281						0.559					
Imp Radiation Degradation	BOL assumed	1.000		0.267						0.535				
Vmp Radiation Degradation	BOL assumed	1.000			4.259						4.240			
Voc Radiation Degradation	BOL assumed	1.000				4.756						4.862		
Cell Operating Temperature (LAPSS PH)	28.0°C													
Isc Temperature Correction	270.1 uA/°C	0.0000 A	0.281						0.559					
Imp Temperature Correction	184.6 uA/°C	0.0000 A		0.267						0.535				
Vmp Temperature Correction	-9.3 mV/°C	0.0000 V			4.259						4.240			
Voc Temperature Correction	-9.0 mV/°C	0.0000 V				4.756						4.862		
Cell-to-Cell Interconnect Voltage Drop	0.01 ohms	-0.0027 V			4.256						4.235			
BOL CIC Performance			0.281	0.267	4.256	4.756	1.13	30.43%	0.559	0.535	4.235	4.862	2.27	30.23%
Cell Stringing Mismatch		0.995		0.265						0.532				
Number of Series Cells per String		30			127.678	142.683					127.048	145.847		

Using the SolAero IMMX+ temperature coefficients DSS calculated the FACT SPM performance when operating at 5 AU and -125 °C after exposure to 5E15 e cm^{-2}. The analysis produced a power scaling factor of $Pmp(-125°C)/Pmp(28°C) = 1.2236$. The estimated EOL power output of the FACT SPM at -125 °C and 5 AU is 3.054 W. The results are displayed in Table 14.

Table 14: SPM EOL Power at -125 °C, 5 AU and 5E15 e cm^{-2}

FACT SPM Power at 28 °C (W)	67.54
ΔT	-153 °C
Cell Pmp at 28 °C (W)	1.193723
Vmp at 28 °C (V)	4.28
ΔVmp for -125°C (V)	1.6371
Vmp at -125 °C (V)	5.9171
Jmp at 28 °C (A)	0.27891
ΔJmp for -125 °C (A)	-0.03205
Jmp at -125 °C (A)	0.24686
Pmp at -125 °C (W)	1.460698
$Pmp(-125°C)/Pmp(28°C)$	1.223649
FACT SPM Power (-125 °C, 5 AU)	3.0544149

DSS performed system level wing mass analysis for wing powers of 10, 15, 25 and 30 kW assuming an array operating voltage of 145.8 V at 28 °C. The detailed mass analysis included all the systems comprising a ROSA array

- FACT SPMs
- Open-weave mesh backplane
- Backplane carbon laminate terminator strips
- DSS Roll-Out Deployable Slit Boom Assemblies and root closeout mechanism
- Boom Deployment System and Synchronization Assembly
- Blanket Tension Assembly
- Harness Assembly for IMBA
- Yoke Panel/Root Structure
- Wing Tie-Down Restraints and Release Devices
- Blocking diodes and diode board

Table 11 provides blanket sizes for the wing powers specified in the paragraph above. One-hundred-millimeter carbon slit booms were chosen for wings having a power level from 10 through 20 kW. One-hundred twenty-five millimeter booms were chosen for wings having a power level of 25 through 30 kW.

Table 15: ROSA Blanket Size as a Function of Power

Power (kW)	Required number of SPMs	Number of Columns	Number of Rows	Blanket Width (m)	Blanket Length (m)
10	150	5	30	2.374	11.864
15	224	5	45	2.374	17.797
20	300	6	50	2.850	19.977
25	374	7	54	3.322	21.356
30	448	7	64	3.322	25.31

The wing specific power for five array sizes is in Table 16.

Table 16: Wing Specific Power for Five Array Sizes at 28 °C and AM0

Wing Power (kW)	Wing Mass (kg)	Specific Power (W kg^{-1})
10.13	45.96	220.43
15.12	68.16	221.97
20.26	88.58	228.74
25.26	112.23	225.07
30.25	134.91	224.28

Table 17 displays the wing specific power at EOL at 5AU at -125 °C after exposure to 5E15 e cm^{-2}.

Table 17: Wing Specific Power at EOL

Wing Power at 28 °C, and 1 AU (kW)	Wing Power at LILT (W)	Array Mass (kg)	Specific Power at LILT (W kg^{-1})
10.13	458.1	45.96	9.97
15.12	684.1	68.16	10.0
20.26	916.2	88.58	10.3
25.26	1142.2	112.23	10.2
30.25	1368.3	134.91	10.1

The stowed power density for five array powers is displayed in Table 18. The NRA goal is 60 kW m^{-3}. At the end of the Base Phase we are at 86% of the goal.

Table 18: Stowed Power Density

Nominal Wing Power (kW)	Stowed Volume (m^3)	Stowed Power Density (kW m^{-3})
10	0.252	40.16
15	0.315	47.95
20	0.392	51.63
25	0.491	51.39
30	0.577	52.40

Section VI: New Technology

APL developed and demonstrated the ability to evaluate solar cell adhesive outgassing due to thermal and UV exposure. This is a powerful tool to enable successful application of concentrator design approaches to space solar applications. APL did not develop any patentable inventions during the Base Phase.

Section VII: Conclusion

We have made good progress in the Base Phase towards achieving the NRA Goals expected at the completion of Option II as restated in Table 19 below. We have confidence that our technology approach will achieve the NRA Goals through continued support in Option I and II.

Table 19: Summary at the End of the Base Phase

Item	NRA Goal	Transformational Array Performance	Percentage of Goal
BOL Cell Efficiency	35 %	33.7 %	96 %
EOL Blanket Efficiency	28 %	28.3 %	101 %
Specific Power at LILT	8 – 10 W kg^{-1}	9.52 W kg^{-1}	95.2 %
Packaging Density	60 kW m^{-3}	51.4 kW m^{-3}	86 %

Signed

Edward M. Gaddy

Edward M. Gaddy

Section VIII: References

[1] A. C. Tribble, "Fundamentals of Contamination Control", SPIE Press, Bellingham, Wash., doi:10.1117/3.38788 , 2000.

.

Appendix: TRL Assessment

Table 20: TRL Assessment for the Solar Array Structures

	Green - TRL 4, 5, 6, 7, 8, 9
	Yellow - TRL 3
	Red - Below TRL 3
	White - Unknown
X	Exists
Y	Yes
N	No
?	Uncertain

System, Component, Subsystem		Demonstration Unit				Environment							
		Component	Breadboard	Prototype	Flight Qualified	Laboratory Environment	Relevant Environment	Space Environment	Operational Environment (Launch/Space)	Analytical Scalability	Manufacturing Scalability	Overall TRL	Rationale for Overall TRL
System: Solar Array (2 kW)		X	X	X	X	Y	Y	Y	N	Y	Y	7	A 2 kW ROSA has been fabricated and tested in an operational environment. The array is partially populated with PV including Spectrolab and SolAero product. The deployment roll out booms are purposely large to demonstrate deployment of a 10 kW array. The wing has deployment control, tie downs, everything. This wing will retract.
System: Solar Array (14.1 kW)		X	X	X		Y	Y	N	N	Y	Y		DSS intends to have this array flight qualified (TRL-8) for Space Systems Loral in September, 2017.
Subsystem: Blanket													
	Full Blanket	X	X	X	X	Y	Y	Y	N	Y	Y	7	A 2 kW ROSA blanket has been fabricated and tested an operational environment.
	Blanket Section (Standard Power Module)	X	X	X	X	Y	Y	Y	N	Y	Y	7	Full size SPMs populated with cells and harness have been fabricated and tested in an operational environment.
	Replacement for heat spreader (stiffener)	X	X			N	N	N	N	Y	Y	3	A coupon with a replacement for the heat spreader, basically a stiffener, is fabricated. Its mechanical function is satisfactory.
	Concentrator Module	X	X	X		Y	Y	N	N	Y	Y	6	The concentrator module for ROSA is at TRL 6. This includes mirrors that are folded for launch and the springs required to place them at the proper angle after the wing is
	Structure (for 10 kW array)	X	X	X	X	Y	Y	N	N	Y	Y	7	The ROSA structure has been fabricated and passed testing in an operational environment

Table 21: TRL Assessment for the Solar Cells

Table redacted.

Table 22: TRL Assessment for Various Array Components

Green	Green - TRL 4, 5, 6, 7, 8, 9
Yellow	Yellow - TRL 3
Red	Red - Below TRL 3
	White - Unknown
X	Exists
Y	Yes
N	No
?	Uncertain

System, Component, Subsystem		Demonstration Unit				Environment							
		Component	Breadboard	Prototype	Flight Qualified	Laboratory Environment	Relevant Environment	Space Environment	Operational Environment (Launch/Space)	Analytical Scalability	Manufacturing Scalability	Overall TRL	Rationale for Overall TRL
Component:	Mirrors	X	X	X		Y	Y	N	N	Y	Y	4	This TRL is difficult to estimate. ROSA has mirrors that are at TRL 6 except that the coating exhibits some delamination after exposure to environments. To get the mirror to TRL 6 requires implementation of well known methods to increase coating adhesion followed by test in an operational environment.
Component:	Reduction of outgassing to acceptable levels	X	X			Y	Y	N	N	Y	Y	4	Initial testing in a laboratory environment suggests that the pre-conditioning the adhesive will reduce outgassing to levels that will not contaminate the mirrors.
Component: Structure Assembly													
	Motor												Motors are not used.
	Deployment Mechanism	X	X	X	X	Y	Y	Y	N	Y	Y	7	A full-size ROSA has been fabricated and tested in an operational environment. This includes the booms that serve as a part of the array's structure as well as to deploy the blanket.
	Deployment Brake	X	X	X	X	Y	Y	Y	N	Y	Y	7	A full-size ROSA has been fabricated and tested in an operational environment. This includes the deployment brake.
	Hinges	X	X	X	X	Y	Y	Y	N	Y	Y	7	A full-size ROSA has been fabricated and tested in an operational environment. This includes hinges.
	Wing tie down	X	X	X	X	Y	Y	Y	N	Y	Y	7	A full-size ROSA has been fabricated and tested in the relevant environment. This includes the wing tie down.
	Mandrel tip	X	X	X	X	Y	Y	Y	N	Y	Y	7	A full-size ROSA has been fabricated and tested in an operational environment. This includes the wing mandrel tip.